AUTOMATED PROCESS MODELLING AND CONTINUOUS IMPROVEMENT

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ABSTRACT

This thesis discusses and demonstrates the benefits of simulating and optimising a manufacturing control system in order to improve flow of production material through a system with high variety low volume output requirements. The need for and factors affecting synchronous flow are also discussed along with the consequences of poor flow and various solutions for overcoming it. A study into and comparison of various planning and control methodologies designed to promote flow of material through a manufacturing system was carried out to identify a suitable system to model.

The research objectives are;

- Identify the best system to model that will promote flow,
- Identify the potential failure mechanisms within that system that exist and have not been yet resolved,
- Produce a model that can fully resolve or reduce the probability of the identified failure mechanisms having an effect.

This research led to an investigation into the main elements of a Drum-Buffer-Rope (DBR) environment in order to generate a comprehensive description of the requirements for DBR implementation and operation and attempt to improve the limitations that have been identified via the research literature. These requirements have been grouped into three areas, i.e.:

a. plant layout and kanban controls,

b. planning and control, and

c. DBR infrastructure.

A DBR model was developed combined with Genetic Algorithms with the aim of maximising the throughput level for an individual product mix. The results of the experiments have identified new knowledge on how DBR processes facilitate and impede material flow synchronisation within high variety/low volume manufacturing environments. The research results were limited to the assumptions made and constraints of the model, this research has highlighted that as such a model becomes more complex it also becomes more volatile and more difficult to control, leading to the conclusions that more research is required by extending the complexity of the model by adding more product mix and system variability to compare results with the results of this research. After which it will be expected that the model will be useful to enable a quick system response to large variations in product demand within the mixed model manufacturing industry.

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List of Acronyms and Abbreviations

ALB	ASSEMBLY LINE BALANCING
BOM	BILL OF MATERIAL
CCR	CAPACITY CONSTRAINED RESOURCE
CI	CONTINUOUS IMPROVEMENT
CONWIP	CONSTANT WORK IN PROGRESS
DBR	DRUM BUFFER ROPE
DES	DISCRETE EVENT SIMULATION
ERP	ENTERPRISE RESOURCES PLANNING
GA	GENERIC ALGORITHM
JIT	JUST IN TIME
KPI	KEY PERFORMANCE INDICATOR
MRP	MATERIALS REQUIREMENTS PLANNING
MRP II	MATERIALS RESOURCES PLANNING
MPS	MASTER PRODUCTION SCHEDULE
MTBF	MEAN TIME BETWEEN FAILURES
OPT	OPTIMISED PRODUCTION TECHNOLOGY
PBS	PROCESS BATCH SIZE
SOP	STANDARD OPERATING PROCEDURES
TBS	TRANSFER BATCH SIZE
TOC	THEORY OF CONSTRAINTS
TQM	TOTAL QUALITY MANAGEMENT
WIP	WORK IN PROGRESS
SLAM II	SIMULATION LANGUAGE FOR ALTERNATIVE MODELLING

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Chapter 1 – Background

1.0 Introduction

It is widely accepted that since the 1980's, industry has been increasingly exposed to international trade. With this exposure comes the need to compete with countries in the global economy that have lower operating expenses, and also the need to cope with an ever increasing demand for high product variety, low volume demand and shorter lead times. In order to compete in this market there are a variety of techniques for improving operational performance that have been extensively employed for increasing the competitiveness of organisations.

1.1 The Need for Flow Processing

Flow processing in manufacturing is a technique that has ultimate aims to produce a product one unit at a time, at a formulated rate, without waiting time, queuing time, or other delays. The ability to produce a product closer to its actual work content time reduces the lead-time and eliminates waste within an organisation considerably leading to higher levels of operational performance.

Lack of flow processing can result in excess inventory (Shingo 1995) and be a major contributing factor to long lead time delays. Hence, key benefits of flow are reduced lead time and work-in-process (WIP) inventory (Hobbs 2000). Other benefits of flow manufacturing include; inventory reduction, quality improvements, improved response time to customer requirements, reduction of working capital to run a business, increased productivity, and improvement in floor-space and capital asset utilisation.

There is a number of planning and control systems within manufacturing designed to enable the implementation and improvement of flow processing within an organisation, i.e. these are shown in Table 1.1.

Table 1.1: Control Systems for Improving Flow

Assembly line manufacturing	Kanban manufacturing
Continuous flow manufacturing (CFM)	Lean manufacturing
Repetitive manufacturing	Agile manufacturing
Just-in-time (JIT)	Cellular or cell manufacturing
Toyota production system (TPS)	Demand flow manufacturing

1.1.2 Requirements for Flow

Traditional flow processing systems are unable to cope with high levels of product, process and demand variability and to operate efficiently since they are designed to achieve the objectives and meet the constraints shown in Table 1.2.

Table 1.2: Limitations of Traditional Flow Process Systems (Khalil 1995)

i. stable demand,
ii. high and limited amounts of production volumes,
iii. limited variability in product mix ratios,
iv. limited range of processes,
v. limited range of tooling,
vi. limited process route options,
vii. continuous production, and
viii. single products or a limited range of products that are similar in design.

1.1.3 Synchronous Flow

Umble and Srikanth (1990) describe systems with non-synchronous flow as having the characteristics of "long manufacturing lead times, and materials spending a large amount of time waiting in queues as work in process". They describe synchronous flow as environments where "processing accounts for a relatively high percentage of the manufacturing lead time for materials". In order to achieve this synchronous flow, the flow of materials through the plant must be carefully coordinated between processing operations, with materials moving smoothly and continuously from one operation to the next.

The basic requirements for establishing synchronous movement of material between successive work areas have been identified by Umble and Srikanth (1990) who proposed a set of fundamental principles which have much in common with the basic rules of Optimised Production Technology (OPT). Achieving synchronous flow requires start and stop times at sequential operations to be co-ordinated. Hence, it is essential that the various components, i.e. Table 1.3, of these cycle times are identified and methods provided to synchronise control at individual work operations.

Table 1.3: Components of Manufacturing Process Times

1. Production time; time spent processing a product.
2. Set-up time; time spent preparing to process a product.
3. Idle time; time not used for either set-up or processing.
4. Waste time; time spent processing materials that cannot be converted into throughput, this may include products of unacceptable quality, work-in-progress materials that are not needed, or end items for which there is no demand.

1.1.4 Problems that Exist with Synchronising Flow

It is well recognised that flow manufacturing must have sources of variability removed or reduced to be effective. The sources of variability that exist in high variety/low volume production systems have been identified by Umble and Srikanth (1990) and are listed in Table 1.4.

Table 1.4: Uncertain variables within a manufacturing system

a) Unstable demand
b) Low and varied range in product volume
c) Unlimited variability in product mix ratio's
d) Unlimited range in processes
e) Unlimited range of tooling
f) Unlimited process route options
g) Discontinuous production
h) Multiple products or an unlimited range of products with a dissimilar design

Such variability sources are often the major causes of the effects listed in Table 1.5.

Table 1.5: The effects of poor synchronisation

1. Inventories are too high (at all stages where the company holds inventory)
2. Lead times are too long
3. Poor customer service, in terms of on-time delivery or service-from-stock
4. Poor productivity
5. Too much overtime
6. Too much expediting
7. Priorities constantly shifting
8. Frequent materials and parts shortages
9. Unable to quickly and easily respond to urgent customer requirements

1.1.5 The Results of Synchronous Manufacturing

In environments where synchronous flow can be operated effectively the results on operational efficiency include:

a. large improvements may be achieved quickly, without implementing improvement projects, capital acquisitions, or floor lay-out changes. Synchronous Manufacturing is tolerant of poor data, inaccurate data and missing data,
b. basic intuitive measurements connect every decision and action in all departments, management use exactly the same rules and measurements,
c. lower inventory, improved flow of material movement, finished goods and WIP inventories are often reduced,
d. shorter cycle times, shorter promised lead times,
e. higher due-date performance or service levels,
f. a more reliable shop schedule that protects due-date performance against disruptions,
g. synchronous manufacturing schedules generally require overtime only to respond to genuine problems or to opportunities to make more money,
h. no sophisticated or expensive computer support usually needed,
i. the approach normally generates acceptance from all managers, all functions, and at all levels,
j. additional capacity is generally achieved in the same resources,
k. clear basis for continuous improvement,
l. provides a framework for dealing routinely with urgent customer demands, and

m. focuses other technologies to implement maximum return on investment.

1.2 Alternative Methods of Planning

The problem of managing physical stocks or inventories is influenced by the manufacturing system structure being used, and the structure of an operating system will largely reflect the nature and location of inventories and how the system is managed. Major approaches (Umble and Srikanth 1990) have emerged in order for manufacturing companies to achieve improved planning and scheduling, i.e. these include Materials Requirements Planning (MRP), Just-in-time (JIT), Assembly-line-balancing (ALB), and the Theory of Constraints (TOC).

1.2.1 Materials Requirements Planning (MRP)

Material requirements planning (MRP), which has evolved into manufacturing resources planning (MRPII) and enterprise resources planning (ERP), is a procedure for determining how much and when dependant demand items should be ordered to satisfy requirements for end items based upon orders combined with forecasts. It uses the assumptions of infinite capacity and fixed lead times and normally deals with large numbers of end items comprising of a large number of components. The evolution of MRP was necessary to include planning and control of additional functions and further integrate other non-manufacturing business functions within the overall planning process.

1.2.2. JIT / The Toyota Production System.

A production management technique, Just-In-Time manufacturing (JIT), or the Toyota Production System, was established in Japan and developed by Toyota in the 1950s and 1960s. There were a number of unique conditions in the Japanese manufacturing environment that led to its development (Hayes 1992), (Womack, Jones and Roos 1990), i.e.:

a) the commitment that Toyota had made to lifelong employment of workers led to subsequent acceptance by the unions of multi-skilling,
b) the premium on space in Japanese plants meant that work-in-process inventory was viewed very unfavourably,
c) the dependence of Japan on external sources of raw materials,
d) lack of access to capital in war ravaged Japan, and
e) the local demand for a wide variety of car models from a low production industry.

These factors led to the development of a production system that stressed flexibility, elimination of waste, quality and worker involvement over the standard Western micro-economic concerns for economies of scale (Rice and Yoshikawa 1982).

It is generally recognised that just-in-time manufacturing will result in a significant reduction of inventories (Lu 1986). Its philosophy on inventory management involves Striving for a zero level of inventories, producing items at the rate required by the customer, eliminating all unnecessary lead times, reducing set-up costs to achieve the smallest economical lot size, and optimising material flow from suppliers through the production process to the point of sale of the finished product so that inventories are minimised. In addition, a total quality management (TQM) program is implemented to ensure that there is high quality and dependable just-in-time delivery from suppliers, minimal scrap and rework, and resultant delays in production.

The JIT aim is to reduce inventory slowly, identify problems, then change policies and practices to remove the problems. In many cases companies try to reduce inventories without resolving the problems, and when production comes to a halt, managers blame JIT. One of the symptoms of this would be supplier shortages (Vokurka, Davis 1996). With use of JIT problems such as machine break-downs, mistakes in production procedures and poor organisation are eliminated through steady, continual effort and team projects that are designed to show benefits in the long term. However, although the philosophy is simple, implementation is often more difficult and the pay-back period for JIT can appear to be a risk because of the time and expense in training and development programs as well as improvement and waste-reduction projects.

1.2.3 Assembly line balancing

Assembly line balancing (ALB) is the term used for assigning tasks to workstations in a serial production system, typically with a single product being produced in high volume with a labour intensive process. Whereas it may be possible to let each workstation produce entire products from start to finish, the ALB philosophy argues that there are advantages to splitting the total production process into a series of stages with a different worker(s) used for each stage. Advantages of a single serial assembly line include:

1. The ability to use a synchronous part entry and transfer mechanism to pace the production rate.
2. Reduce training requirements as each worker need only learn a subset of tasks.
3. Shorter cycles usually have a faster learning curve, i.e. greater reduction per cycle.
4. Less time for workers to get up to speed, i.e. speed = the required Takt time.
5. Reduced capital cost because each task is performed at a single workstation thus avoiding the need to duplicate tooling.
6. Elimination of set up time that might otherwise be required if workers constantly switch back and forth between tasks, (Askin and Goldberg 2002).

1.2.4 Theory of Constraints and Drum-Buffer Rope

Drum-buffer-rope is an operational scheduling and controlling methodology based on TOC that balances the flow of the production system by controlling the flow of material through the plant in order to produce products in accordance with market demand with a minimum of manufacturing lead-time, inventory, and operating expenses. In doing so, it concentrates on managing the flow of products to meet the bottleneck constraint's needs. Since the bottleneck pace determines the systems throughput, managing the bottlenecks throughput manages the system's throughput.

To maximise the system's throughput, the bottleneck must utilise all of its available capacity. Similar to the MRP/MRPII systems, the DBR system uses a scheduled release of products to control the production rate, and a safety stock or buffer at the bottleneck to guard against variability from the upstream workstations (Nicholas1998).

A manufacturing system is required, that is able to cope with variability and still maintain a synchronous flow, without the need for excess inventory. Low demand volume in manufacturing does not affect the ultimate aim of flow, which is to produce a product one unit at a time, a system that has the potential to deal with the logistics of synchronous flow and cope with high variability is the Drum-Buffer-Rope philosophy devised by Goldratt (1990).

1.3 Previous Research

Previous research has been carried out in order to compare the various methods of planning and control that are currently in use in the manufacturing industry.

1.3.1 DBR v MRP location of buffers

Duclos and Spencer (1995) based a simulation of MRP and DBR on an actual operating production environment and until that date, there had not been an analytical study of a full DBR method to support the theory that a strategically placed buffer in a "T" logical structure, or flow shop will improve the performance of the manufacturing system. Their study indicated that DBR produced significantly better results than MRP methods used at the factory.

1.3.2 TOC v MRP location of buffers

(Lambrecht and Segaert, 1990) identified DBR as a "*long pull*" system because a fixed level of inventory is maintained in the system; the materials to produce one piece are pulled into the system as a completed piece is shipped. A comparison was made between DBR and the Kanban system, where each operation has a small level of inventory with a fixed maximum, and production is pulled from one operation to the next. The small fixed buffers provided less protection from variability upstream of the constraint resulting in more late shipments and lost output.

1.3.3 TOC v JIT performance (subjective)

A survey-based comparison of performance and change in performance of firms using traditional manufacturing, JIT and TOC was carried out Sale and Inman (2003).

The conclusions were that TOC had significantly higher performance and performance improvement when compared with those using JIT and traditional manufacturing. The results of the research did not demonstrate that JIT was superior to traditional manufacturing as in other studies, but it showed that JIT was slightly behind traditional methods in both performance and performance improvement, although it was not significant.

1.3.4 JIT v ALB inventory

The performances of lines designed using the traditional western approach to line balancing compared to the JIT approach was examined by Chakavorty and Atwater (1995) using a simulation package; SLAM II developed by Pritsker (1986). The simulations indicated that when inventory in the system was high, JIT achieved a lower cycle time, and when system variability was low JIT achieved a lower cycle time than a traditionally balanced line apart from when the system inventory was very low. They concluded that when inventory levels were low the traditionally balanced line out performed JIT, but with sufficient inventory, JIT was superior.

1.3.5 Output flow control v bottleneck control v dynamic flow control

An investigation of output flow control, bottleneck flow control and dynamic flow control mechanisms in various simple line scenarios was carried out (Kim et al.2003). The research compared three approaches to flow control and the performance of each flow mechanism was measured at above 95% production capacity to ensure that the system was constrained, and that there was little or no extra protective capacity to respond to variations in the line. The use of a five operations, five stations unbalanced serial line was made to conduct the comparison analysis and the experiments were conducted using the simulation package SLAM II, and eight experiments were carried out. Output flow control was modelled after CONWIP and bottleneck flow control was modelled after Drum-buffer-rope. Dynamic flow control is a demand-pull based mechanism designed to respond to customer demand in a timely manner, whilst controlling WIP levels at each work centre. It seeks to provide a constant flow of material through a line at specified target production rate.

They concluded that the impact that a flow control mechanism can have on performance is dependant on the characteristics of the line, and therefore, when employing a flow control mechanism, the characteristics of the line (location of breakdowns with respect to the bottleneck, location of the bottleneck, variations in processing time) should be identified. The results indicated that although CONWIP is more favourable than dynamic flow control, the drum-buffer-rope flow control mechanisms are superior for simple production environments.

1.3.6 JIT v TOC v ALB downtime, process time and inventory variability

Further investigations by Chakravorty and Atwater (1996) was carried out when a balanced line, JIT and TOC (drum-buffer-rope) approach was simulated for comparison, again using SLAM.

The results showed that at low levels of variation at a workstation JIT performs best if there is sufficient inventory, and at high levels of variation TOC performs best. The downtime results revealed that when station downtime is relatively high, TOC performs best, and when they are low, JIT performs best. The inventory results indicated that with low levels of inventory, TOC performs best with JIT and balanced lines performing equally as well as each other, but as the inventory level was incrementally increased, the JIT line improved until it out performed TOC with the balanced line trailing behind. The concluding results of these simulations revealed that TOC lines will significantly out produce both JIT and balanced lines at relatively low levels of system inventory, and also that TOC lines achieve there maximum output level with much lower levels of inventory in the system. JIT lines will significantly out produce TOC and balanced lines if there is sufficient inventory.

In summary, each line was subjected to different combinations of variability in; downtime, process time and inventory levels, and their conclusions were as listed in Tables 1.6 to 1.8.

Table 1.6: Inventory variability

1. TOC lines will significantly out produce both JIT and balanced lines at relatively low levels of total system inventory. 2. TOC lines will achieve their maximum output level with much lower inventories in the system than JIT lines. 3. With sufficient inventory, the JIT line will significantly out produce both TOC and balanced lines.

Table 1.7: Process variability

1. TOC lines perform best when station variation is relatively high. 2. JIT lines perform best when station variation is relatively low, and is the most heavily affected by changes in station variability.

Table 1.8: Down-time variability

1. TOC lines perform best when station down-time is relatively high. 2. JIT lines perform best when station down-time is relatively low.

Previous research comparing the main types of manufacturing planning and control systems, point to the TOC/DBR method to be a good candidate for improving the throughput of a system with a high product variety and low volume demand requirement.

1.4 Chapters Overview

Chapter 1explains the need for production flow and the consequences of poor material flow through a manufacturing system, and the system requirements that enable good flow with a brief overview of synchronous flow manufacturing. Industry has attempted to achieve material flow in various ways and included in chapter 1 is a brief overview of some of the alternative methods of production planning.

Chapter 2 leads on to the complexities of synchronous flow and the factors that can affect it in various ways at various times, conditions and points within a manufacturing system. Each factor is examined including the conflict of increasing production batch sizes to reduce change-over time with the result of long queuing time or to reduce the batch sizes which in turn causes lost process time due to change over times. Within each factor examined are methods designed for overcoming poor flow such as Kanban and other forms of material control, and it can be seen that there are common characteristics in all the methods that must be used to achieve it. Also within this chapter is a critical overview of the OPT, TOC and DBR methodology and a comparison between TOC and MRP with the characteristics for synchronous flow.

Chapter 3 critically reviews the research literature for DBR methodology against other production planning methods and critically examines each operational component for DBR and each of its five planning methods for implementation in detail and the various techniques researched for achieving those methods; concluding with a detailed analysis of the benefits and limitations that were identified including the failure mechanisms that are available to be addressed.

Chapter 4 develops an experimental plan, using Taguchi orthogonal arrays for identifying the relationships between pairs of metrics, using correlation analysis. A discrete event simulation model is developed for a DBR system and used to generate the experimental results. Chapter 5 reports the results of the simulation experiments, and draws attention to key relationships.

Chapter 6 draws together the key concepts of the thesis for the removal of the DBR failure modes that have been identified and addressed by the results of the model and also the factors that have been identified by the model that affect system throughput and process synchronisation.

Chapter 7 draws the conclusions of the research and lays the ground for further research.

Chapter 2 - Promoting Synchronous Materials Flow

2.1 Introduction

In high variety/low volume (HV/LV) batch manufacturing environments queuing time normally represents the greatest proportion, i.e. up to 90% of the total processing lead time. Queue times for specific jobs are dependent on such factors as current work-in-progress loads, machine breakdown frequencies and repair times and the frequency of set-ups (Papadopoulos et al. 1993).

The effect of such factors varies from production period to period due to changes in product mixes and customer demand levels, and hence queuing times may be difficult to accurately estimate. HV/LV batch manufacturing environments are, therefore, characterised by disconnected or non-synchronous flow of materials between processes due to jobs spending unpredictable, and often long, periods of time in queues waiting as work-in-progress. Such interruptions in materials flow between and during processing normally results in long manufacturing lead times (Fry, 1990).

Synchronised flow is characterised by products that have relatively short manufacturing lead times, and significantly shorter periods queuing as work-in-progress, (Umble and Srikanth, 1990). When compared to non-synchronous flow environments, value added processing time within synchronous flow environments accounts for a relatively high percentage of the overall manufacturing lead-time for products. Promoting synchronous flow within HV/LV environments would, therefore, lead to increases in value added time and hence would prove beneficial in improving the efficiency of such systems.

This chapter begins by identifying the factors that influence synchronous flow and eventually analysing their applicability within traditional batch manufacturing environments.

2.2 Factors Affecting Synchronous Flow

A number of researchers have identified the factors, Table 2.1, to consider whilst attempting to promote synchronous flow within manufacturing, including, Umble and Srikanth (1990), Wild (1995), and Fisher (1995). Sections 2.2.1 to 2.2.8 examine the management activities influencing these factors.

Table 2.1: Factors Affecting Synchronous Flow

i. Facilities Layout, i.e. positioning on the shop floor of individual items of processing equipment.
ii. Production Schedules, i.e. the order jobs are processed at individual processes.
iii. Inventory Management, i.e. the position and quantities of inventory available on the shop floor.
iv. Process and Operator Flexibility, i.e. the ability to change the level of capacity available, e.g. by use of multi-skilled operators and/or adding items of processing equipment.
v. Batch Sizes, i.e. the batch sizes that are processed.
vi. Capacity Management, i.e. the levels of available production capacity.
vii. Process Reliability & Capability, i.e. the capability of processing equipment to consistently produce the quality levels required.
viii. Lean Practices & Standardisation, i.e. the level and type of waste reduction enablers and standard operations procedures used on the shop floor.

2.2.1 Facilities Layout

In terms of facilities layout synchronous flow is assisted by ensuring that short distances are provided between sequential items of equipment, i.e. this reduces both handling costs and times and enables smaller batch quantities to be transferred between items of equipment without excessive transport costs arising. In addition, there should be a high level of visibility between operators to ensure that disruptions to flow, caused by such problems as machine breakdowns or material shortages, are quickly identified and countermeasures put into place (Black, 1991).

Other factors that promote synchronous flow are (i) the availability of small amounts of buffer stock between processes such that slight variation in cycle times and/or work rates can be accommodated without blocking and waiting arising to disrupt material flow(Dallery and Gershwin,1992), and (ii) the existence of balanced work loads and/or equal cycle times at individual processes such that one process completes its work at the same time that succeeding processes are ready to start the next job, i.e. all processes start and finish at the same time (Burbidge, 1975).

Within discrete parts production two basic types of layout have been developed and are in common use within industry. These are:

i) Process layouts in which all items of equipment that perform the same or similar operations are grouped together on the shop floor, i.e. process layouts group similar types of operations together into functional work areas or departments, (Stockton and Lindley, 1995). Each batch or job is routed through these production areas according to their routing sequence of operations. This layout type is preferred for batch manufacturing since it provides the high levels of planning flexibility required to cope with the high levels of product variability and small variable batch sizes that exist (Wainwright, et. al 1993). However, this level of planning flexibility is normally achieved at the expense of the factors that promote synchronous flow, i.e. long distances and lack of visibility between sequential processes, large batch sizes and varying batch cycle times at processes (Parnaby, 1988).

ii) Product layouts in which items of equipment required to manufacture a single or group of similar part types are laid out on the shop floor in the order they are required to process these part types, i.e. all the required operations for producing a product are arranged in a flow processing or assembly line (Garcia-Diaz, 2007). This layout is specifically designed to promote synchronous flow since items of equipment are normally placed as near as possible to each other to enable small quantities of materials to be transferred in single lots. In addition, there are high levels of visibility between adjacent processes and cycle times and/or work loads on the individual items of equipment that make up the product layout are balanced (Hopp and Spearman, 1991).

However, in achieving balanced lines the levels of product variety such lines can cope with is greatly limited when compared with the use of process layouts (Nicholas 1998).

2.2.2 Production Scheduling

The primary aim of production scheduling is to ensure that customer order due dates are met without the use of excessive amounts of production capacity and materials, (Gupter, 2002). In achieving this aim the production scheduling function must seek to achieve the objectives listed in Table 2.2, (Khalil, 2005).

Table 2.2: Internal Objectives of Production Scheduling

i. Reduce manufacturing lead times. ii. Increase the utilisation of resources through use of large batch sizes to reduce lost capacity through change-overs. iii. Increase throughput of items that can immediately be sold and minimising those items that are destined for finished goods inventory. iv. Reduce inventory costs by reducing processing batch sizes. v. Reduce direct and indirect labour costs and operating expenses.

Increasing capacity utilisation by increasing processing batch sizes (and hence less time lost to change-overs) can lead, therefore, to long queuing times whereas reducing batch sizes to reduce inventory levels results in greater numbers of change-overs being required which again cause delays in processing, (Sohal, and Howard,1987). Despite these conflicts between the objectives of production scheduling and the factors that promote synchronous flow the production scheduling function can assist, (Umble and Srinkanth, 1990), by:

a. ensuring where possible that completion of a job on one machine coincides with the start of a new job on the next machine,

b. balancing capacity usage at processing resources, i.e. preventing delays throughout the system due to insufficient capacity and/or resource skills at individual processing areas.
c. ensuring that inventory levels at strategic points in the system are sufficient to prevent manufacturing stoppages due to lack of materials.
d. ensuring that the levels of materials being processed do not exceed the capacity of the system, and
e. ensuring that the completion of product dependant parts and processes coincide at the correct time and point for assembly, i.e. all bill of material for assembly are scheduled and processed so they are available at the correct quantity and time at the assembly point, (Sivasubramanian et. al. 2000)

However, in order to achieve the above aims, the production scheduling process, which is essentially a decision making process, requires specific information and a low level of production disruptions in order to achieve scheduling solutions that promote material flow. (Umble and Srinkanth, 1990), for example, found it is essential that:

a. Knowledge is available in terms of which jobs need to be included in a schedule, i.e. with HV/LV there are frequent changes in customer demand, delivery requirements and product mix.
b. Knowledge of the criteria to be used to select an optimum schedule, i.e. relevant criteria, identified in table 1.3 chapter one are often difficult to identify or may change over time, some support synchronous flow and others prevent or deter synchronous flow (Harrison, 1987).

2.2.3 Inventory Management

Conway, et al. (1988), demonstrated the role of work-in-process inventory in serial production lines, and highlighted its importance for synchronous flow as a buffer to process variability. To achieve a continuous process flow, buffer inventory must be held between process stages to avoid running short in the event of demand or lead-time variability. It was found to be important to ensure that buffer stock is managed to ensure that it is positioned at the correct locations and in sufficient amounts to cope with the effects of the system product and process variability whilst preventing a build-up of unnecessary inventory. Ensuring that production flow is continuous requires inventory being available to each process at all times during its activation, i.e. no stock shortages must occur (Vollmann, 2005).

Consideration, therefore, must be given when planning inventory levels to offset the effects of the lead-time and demand uncertainty that exists within HV/LV environments (Hopp and Spearman 1991). Here variability may exist in terms of (i) manufacturing process times due to such factors as equipment breakdown, operator absenteeism, and/or the need to process mixed model options, (Umble and Srikanth 1990), (ii) in the quantities produced due to quality issues, (Ramudhin et. al, 2008). In addition, variability can arise in material availability, leading to shortages, through a variety of reasons such as poor supplier reliability, inaccurate forecasting and other information supplied to the system (Sohal and Howard, 1987). In all cases achieving synchronous flow can be disrupted.

2.2.4 Batch Sizing

It is generally recognised that in HV/LV manufacturing environments that processing in batches generates queuing time and that this time represents the greater proportion of the total manufacturing lead time. Moreover, as batch sizes increase, so then do queuing times and as a result manufacturing lead times and costs. The size of the processing batch is therefore a fundamental factor that determines the efficiency of a manufacturing area in terms of its throughput levels and levels of work-in-progress (Wild, 1984).

The effect of large batch sizes on a system is to increase queuing time and, therefore, waiting time which disrupts synchronous flow and increases work-in-progress. Large batches are most effective, (Belyalov and Khabibullin, 2005), with standardised, i.e. less diverse, product ranges, manufactured in larger quantities and with fewer types of end products and less changeovers. The effect of small batch sizes on a manufacturing system, if changeover times are short or do not exist, is to reduce queuing and waiting time and increase synchronous flow, resulting in shorter lead times, (Umble and Srikanth 1990).

Within a HV/LV environment the arguments for increasing processing batch sizes are that machine utilisation is increased and handling costs are reduced. Arguments for reducing batch sizes include reductions in queuing times and inventory costs, and quality problems becoming more obvious sooner and hence can be removed before large amounts of defective items have been produced, as would occur if quality checks were only undertaken after fully processing a large batch of items (Hopp and Spearman 1991).

In general it is considered more beneficial to reduce batch sizes and offset increases in handling costs by introducing product based plant layouts that minimise handling distances between work areas (Meller and Gau, 1996).

Goldratt, (1980), when describing the Optimised Production Technology, (OPT) philosophy, highlighted the false economy of maximising the utilisation of non-bottleneck resources. Here capacity was wasted producing more parts that the system could convert into finished goods. In addition these parts added to inventory costs. OPT seeks to utilize non-bottleneck resources only sufficiently to maximise the utilisation of bottleneck resources, i.e. not by increasing batch sizes but by improved priority scheduling of these resources.

Arguments also exist, (Umble and Srikanth 1990), that suggest that lowering batch sizes will have little effect on queuing times since in HV/LV environments processing batch sizes already tend to be low. Hence, the effect of reducing batch sizes may not have a significant effect on reducing queuing times. However, optimum batch sizes need to be identified particularly with respect to the efficient use of bottleneck resources (Plenert, 1999). In conventional manufacturing systems, the process batch size, i.e. 'the quantity of items processed at an item of production equipment, is normally calculated using Economic Order Quantity (EOQ) models'. However, in terms of promoting synchronous flow a second type of batch needs to be considered, i.e. 'the transfer batch, which is the quantity of items from the process batch size that during processing are transferred to the next operation'.

Transfer batch sizes need not be the same as Process batch size. However, if these batch sizes are the same then each process batch is fully completed at each operation before proceeding to the next, which may result in long lead times and the associated high inventory costs. If, however, the Transfer batch size is smaller than the Process batch size then items can be processed at the next operation whilst the remaining parts are being processed at the previous process, i.e. parallel processing occurs which could result in greatly reduced lead times and inventory costs (Umble and Srikanth 1990).

2.2.5 Capacity Management

According to Hopp and Spearman (1991), "in most cases, releasing work into a system at or above the capacity causes the system to become unstable", where 'unstable' is defined as the unrestricted build up of work-in-progress (WIP). They found that not exceeding the systems capacity is an important requirement for promoting material flow, i.e. *"In steady state, all plants will release work at an average rate that is strictly less than the average capacity"*.

Capacity planning provides planners with details of the capacity requirements needed to process the planned order releases. Schedules carry detailed information about the order in which jobs should be processed. In practice with finite loading, schedules become out of date frequently due to the many unpredictable events occurring on the shop floor. Hence, the resources used to keep track of which jobs are on schedule and to prepare finite loaded schedules are often wasted, (Maes and Van Wassenhove, 1991). A planned event such as maintenance schedules or holidays is required information for the production schedule to identify the resource availability for capacity planning, but within HV/LV environments planning frequently fails to do so particularly in the case of unplanned events (Khalil, 2005).

Infinite loading through ignoring the capacity limitations of work centres could result in schedules being produced that attempt to load more than one job at a specific work-centre at the same time. The problem of which job to process first is then left to shop floor management to decide. If there is insufficient capacity at a workstation or cell, it becomes a bottleneck operation, which results in blocking and waiting. This has a negative effect on synchronous flow due to the build up of WIP preceding the bottleneck workstation and the inactivity of the work stations after the bottleneck. Holding excessive capacity, if used, can result in over-production, i.e. excessive inventory, or if not used, excessive idle time and poor utilisation of resources (Goldratt, 1980).

Capacity decisions have been found, (Chan, 2005), to have both a direct effect on manufacturing costs and an indirect effect on manufacturing performance by influencing planning and control problems. Capacity management is, therefore, necessary to carry out line balancing, designing new production lines, modifying existing production lines, and is a fundamental requirement in the planning and scheduling of a plant (Umble and Srikanth 1990).

2.2.6 Process Reliability & Capability

The process reliability of an item of equipment is a measure of its ability to perform within its normal operating conditions, i.e. the higher the reliability level then the less likely an item of equipment is to fail. Failure can range from the equipment simply malfunctioning, i.e. slowing down, minor stoppages to completely breaking down. This unscheduled downtime and process rate change is a source of process time variability which causes a disturbance to flow and hence hinders synchronous production (Al-Najjar, 1996).

Nakajima, (1988), identifies 'production losses' due to the effects of equipment reliability, i.e.:

i. Equipment failure losses which are categorised as time losses when productivity is reduced, and quantity losses caused by defective products.
ii. Set-up/adjustment time losses which result from down time and defective products that occur when production of one item ends and the equipment is adjusted to meet the requirements of another item.
iii. Idling and minor stop losses which occur when the production is interrupted by a temporary malfunction or when a machine is idling.
iv. Reduced speed losses which refer to the difference between equipment design, speed and actual operating speed.
v. Reduced yield which occurs during the early stages of production from machine start to stabilisation.

vi. Quality defects and rework which are losses in quality caused by malfunctioning production equipment.

With long term planning the frequency with which disruptions to planned events take place are normally at their greatest, hence production schedules can frequently change. This happens regularly in HV/LV manufacturing environments, where the types of unplanned events listed in Table 2.3 may frequently occur.

Table 2.3: Unplanned Events that Disrupt Production Schedules (Khalil, 2005)

a. machine breakdowns,
b. variability in operator work rates,
c. bad quality,
d. changes in customer orders,
e. unreliable suppliers, and
f. employee absenteeism.

Normally within HV/LV environments the final details of a schedule are fixed only immediately prior to its release to production in order that the most recent disruptions to manufacturing can be taken into consideration. Often, therefore, the optimum use of manufacturing resources such as labour equipment and tooling cannot be achieved.

In order that the manufacturing resources of an organisation can be used effectively through synchronous flow the scheduling function must maintain a system that is capable of developing efficient schedules and must know what criteria are important in determining the efficiency of a schedule. These criteria are varied in nature and importance, and change over time leading to difficulties in ensuring that the best criteria are being used to develop schedules, (Chandra and Kumar, 2000). Unplanned events disrupt synchronous flow and are a cause of blocking and waiting and increased work-in-progress. The frequency with which disruptions to production operations occur make it necessary to have a more responsive scheduling mechanism than the planning process which is normally updated on a weekly basis (Ho, 2007).

2.2.7 Process and Operator Flexibility

Flexibility, (Cheng et al. 1997) is the ability of a manufacturing system to quickly and economically:

a. change between existing part types,
b. change the operation routes of components,
c. change the operations required to process a component,
d. change production volumes, i.e. either increase or decrease,
e. add new part types, and/or
f. add new processes to the system.

An extensive survey was carried-out by Sathi and Sathi (1990) of the manufacturing literature involving flexibility and identified the various types as shown in Table 2.4. Their definitions are in agreement with Browne (1984).

Table 2.4: Definitions of Flexibility Types

Flexibility Type	**Definition**
Machine	The various types of operation that a machine can perform without requiring excessive operating changeover costs and/or times
Material handling	The ability of the material handling system to move part types efficiently through the system
Operation	The ability of a part to be produced in different ways
Process	The set of part types that a system can produce without major set-ups
Product	The ease with which new parts can be introduced into the system or substituted for existing parts
Routing	The ability to produce a part using different process routes
Volume	The ability to operate profitably at different output volumes
Expansion	The ease and capability to expand volumes as needed
Production	The universe of part types that can be produced without the need to purchase new equipment
Programme	The ability of a system to operate untended for additional shifts
Market	The ability of a manufacturing system to adapt to changing market environments

A need for flexibility classification was also identified by Slack (1987) and also Stockton et al. (2005) in terms of:

i) *"range flexibility, i.e. the total envelope of capability or range of states which the manufacturing system is capable of achieving. This is primarily short term flexibility,*

ii) *response flexibility, i.e. the ease, in terms of time and/or cost, with which changes can be made within the capability envelope. This is primarily long term flexibility."*

Within a manufacturing system both Process and Operator flexibility is essential for maintaining synchronous flow. Forms of flexibility required to promote synchronous flow include short set-up times, excess capacity at feeding stations for use as buffers against variability at subsequent processes, excess flexible labour capacity for moving between processes depending on where this extra capacity is required, part built inventory that can be customised at short notice, i.e. flexible inventory, and cellular manufacturing which brings benefits in manufacturing environments that require high levels of product and process variety.

2.3 Material Control Methods

A variety of methods for controlling the flow of materials through manufacturing systems are currently in use. Of these the most popular are Materials Requirements Planning, Pull Kanbans, Constant Work-in-Progress (CONWIP), (Hopp, and Spearman, 2000), Periodic Pull Systems, Push Kanbans, Group Technology, Period Batch Control, and Kitting (Wild, 1984). In addition, there are a variety of constraint based material flow control methods including Buffer Management, Optimised Production Technology (OPT), Theory of Constraints (TOC) and the Drum-Buffer-Rope (DBR) method (Bicheno, 2000). This section briefly examines each of the above methods with the aim of identifying those that are most suited to promoting synchronous materials flow.

2.3.1 Material Requirements Planning (MRP)

The MRP process identifies the orders that must be placed on both the manufacturing facilities and suppliers for the assemblies, components and raw materials that are needed to assemble the quantities of finished products listed on the Master Production Schedule (MPS), (Miltenburg, 1997). The MRP process also identifies the time at which material orders should be placed with suppliers or on the shop floor such that finished goods stock can be made available on the dates requested by the customer or the MPS, (Wild, 1984). MRP is, therefore, used to generate order schedules for the replenishment of made-in and purchased items and raw materials. The variety present in products, batch sizes, lead times and set-up times makes the use of MRP an essential planning and control tool for use within a high variety/low volume manufacturing environment, (Stockton and Lindley, 1995). In this respect many of the problems associated with the successful introduction of MRP systems within industry are related to the level of accuracy with which data is maintained. Hence, the need for rigid working procedures which must be implemented, (Muhlemann et al. 1993), to ensure that any event that MRP should be aware of is entered into the computer accurately and in good time.

In terms of its ability to promote synchronous materials flow within HV/LV environments MRP is limited, (Umble and Srikanth, 1990), in the following ways, i.e.:

i) Implementing and using MRP systems requires a behavioural change on the part of the management and workforce that requires a high degree of sequencing and schedule and process adherence control over each job on the shop floor to ensure its progress through to completion. The level of control required for synchronous flow is often difficult to obtain.

ii) Shop floor information may have to be passed back by operators who may then not have sufficient time to perform their allotted tasks, hence increasing levels of cycle time variability.

iii) Disciplined working procedures, which are again difficult to achieve, are required to maintain a high level of accuracy of the data within the MRP database in a timely manner.

iv) Frequent data inputs are required from the shop floor to ensure the MRP database represents the current state on the shop floor.

Overall, Nicholas, (1990) found that frequency of collection and the amount of information required to maintain sufficient MRP data accuracy was difficult to achieve. Hence, the planning data output from an MRP system is normally out of date and unreliable for synchronous planning purposes.

2.3.2 Kanban Controls

Kanbans, pioneered by Ohno (1988), are visible signals that control material flow through a manufacturing system. Kanbans are cards or containers that are used to control material movements by acting as a signal or method of communication from downstream operations that need more materials. A Kanban signal, therefore, initiates the flow of materials through the shop floor without the need for extensive work-to-lists, schedules and operation sequence shop floor documentation. They also ensure that materials move only when they are required, in the planned quantities and part types, and are moved to the planned work centres.

Kanbans, therefore, represent ‘pull’ signals in that an operator signals the upstream process in the cell, thereby ‘pulling’ the material forward at the rate of its use, Hence demand for output from a preceding process is generated by its succeeding process. The removal of inventory at the preceding stage results in an empty Kanban container which then acts as the signal to authorise the manufacture of additional units to replace those just taken. No manufacturing, therefore, occurs without such Kanban authorisation. As a result, each stage is said to produce the part type and quantity to meet the demand needed by succeeding stages. Controlling the final product demand at the last manufacturing stage or finished goods warehouse, therefore, controls all preceding manufacturing processes.

Using Kanbans the processing and flow of material can be synchronised along the production stages to the rate at which units of end products are produced. However, this is only true for environments where medium to high product volumes are being processed with low product variety and short change-over times between product types. Where higher levels of product and process variety exist, Kanbans fail to cope even when the Kanban signalling process becomes more complex, i.e. when 2 card, production and replenishment kanban control cards are introduced, (Berkley, 1992). In practice either buffers for each part type need to be maintained between processes or Kanban signals must wait until time is available at a process to act on its signal. Hence, material flow becomes disconnected and unsynchronised.

2.3.3 Constant Work In Progress (CONWIP)

Pull type systems that have been used in non-repetitive manufacturing environments generally adopt elements of MRP and Kanban. One such system developed by Spearman et al (2000) is the CONWIP system and has been found to be, in general, more applicable to systems that need to process higher varieties of products. As with

Kanban systems; CONWIP assumes that parts are moved in standard containers, with each 'part type' container holding an equal number of parts. CONWIP relies on signals, usually Kanban type cards, to control the system. The cards are attached to the standard containers and traverse the entire production line with the container. The cards then return to a card queue at the beginning of the line and wait there until being attached to another container. In this way, the amount of material in the system, at any one instance is controlled, by the number of cards issued.

CONWIP differs in its use of cards from traditional Kanban systems in that they are not component specific, (Spearman et al. 1990). Component numbers are assigned to the cards at the beginning of the line and are matched together by referencing a backlog list. The first component number on the list is the first one that should enter the system. The time the part enters the system is also noted on the card. The backlog list is maintained by the production control staff and should be produced from the master production schedule of the MRP system. No production can be started without a card present even if the first process is idle. Although CONWIP is designed for a higher variety of products, it is still aimed at medium to high volume manufacturing as its control strategy is aimed at limiting the total number of parts in the system, (Bicheno, 2000). However, once in the system there is little control over the levels of synchronisation between processes.

2.3.4 Periodic Pull System

A periodic pull system as described by Kim (1985) is a computerised material management system that, at regular intervals, reviews the status of material flow at all processing stages, termed review periods. As a result of a review, only the exact amount of material that has been consumed at a succeeding stage, since the last review time, is allowed to be withdrawn from or produced at a preceding stage. The withdrawal and production operations begin immediately after a review has been performed. This method is not able to control the start and finish times of individual processes in sufficient detail and with sufficient frequency such that synchronised material flow is possible within the system.

2.3.5 Push Kanbans

Push Kanbans, (Weiss 1988), are an enhanced MRP system in which daily capacity requirements planning is carried out for individual work centres within a manufacturing system such that work loads are balanced between manufacturing areas. Each job is allocated a planning card which is located on scheduling boards to prioritise jobs. Marked shop floor areas in front of individual items of processing equipment are used as buffer areas normally for two incoming and two outgoing batches. These areas act as 'regulators', where materials are 'staged through' rather than stored in them. This system acts as a 'push Kanban', i.e. materials are pushed into the incoming area which can only contain a limited number of jobs hence providing a physical constraint to work-in-progress levels. As such no attempt is made to synchronise the movement of materials between processes (Stockton and Lindley 1995).

2.3.6 Cellular Manufacturing & Group Technology (CM&GT)

CM&GT involves the production of a part family, in one particular shop floor area, containing the necessary equipment resources for fully processing all part types within the family, thereby promoting one-piece flow and hence reductions in lead time and inventory. CM&GT classification and coding systems, (Black 2000), enable the identification of product families such that numbers of CM&GT areas are minimised. It also enables decentralised scheduling in which each cell is treated as a single work centre within which detailed scheduling and quality, maintenance and inventory control are the responsibilities of the cell, CM&GT, therefore, assists in enabling one-piece flow, process responsiveness, and visibility, simplicity of control, high quality and minimal inventories, all of which are characteristics that may help to promote synchronous materials flow. Essentially CM&GT aims at the advantages of mass production and the assembly line, i.e. efficiency and one piece flow, without its disadvantages of inflexibility, i.e. CM&GT is a hybrid between the assembly line and the job shop, (Burbidge 1988).

Since one cell is responsible for one product family, volumes must be sufficient for this to be feasible. This may require selecting only the highest volume products or changing existing product routings to enable them to be made within the cell. This could be a problem for use in a HV/LV environment where the low demand for products would not make the cells efficient and where variety is an essential requirement for business that cannot be reduced. Hence, it is difficult to use CM&GT to promote synchronous flow within HV/LV environments.

2.3.7 Period Batch Control (PBC)

PBC, (Burbidge 1988) and (Steele and Malhotra, 1997), is a single cycle ordering system in which a set of standard orders are issued at a series of regular intervals for completion by a complementary series of due dates. PBC was developed to be employed in conjunction with Group Technology and enables:

a. balanced workloads to be allocated to GT cell's,
b. parts to be made in small batches, hence helping to reduce stock levels,
c. set-up times to be reduced, since ordering in 'period sets' makes 'sequencing' in tooling families possible,
d. stock holding costs to be reduced, through holding less stock, and
e. operation scheduling to be simplified, since there is one common due date, and low numbers of machines and parts within each group.

In terms of promoting synchronous flow within HV/LV environments PBC fails to cope with changes in order priorities due to its rigid planning process. It, therefore, often requires spare parts inventories from which parts for high priority orders can be obtained and replenished in the next period. Synchronous transfer of material between processes is only possible if preceding processes finish the jobs before the transfer time. However, PBC prohibits worker flexibility since operators are dedicated to specific tasks each period. PBC also leads to additional buffer inventory in the system in order to avoid blocking or starving of processes. Hence, within a HV/LV environment PBC would not be practical to maintain the high levels of inventory required to cope with levels of variability that frequently occur.

2.3.8 Kitting

A kit of parts represents the complete set of those parts within the bill of materials required for a final product or assembly. Kitting, therefore, involves collecting these components together, placing them in an appropriate container and moving this container between processes in order to reduce material handling costs. Ding and Puvitharan (1990), state that a successful kitting system should:

a. eliminate search time, through all needed parts being present with a specific container,
b. improve control over WIP, i.e. through a focus on reducing the number of kits in process,
c. improve shop floor control, and
d. reduce material handling by sending a kit of parts rather than individual parts to processing stations.

In terms of promoting synchronous flow within HV/LV environments ‘kitting’ often fails due to parts shortages occurring in individual ‘kits’. When this occurs; processing, and hence material flow, is disrupted whilst these part shortages are resolved. Such parts shortages in kits at assembly areas have been found to cause production stoppages particularly in low demand volume environments where replacement kits may not be available, (Henderson and Kiran 1993). Kitting would also add to the already higher costs of purchasing in low volumes due to the non-value added kitting and kit inspection operations that are required.

2.3.9 Constraint Based Control Systems

Constraint Based Control (CBC) systems make use of constraint resources to generate a schedule such that the capacity utilisation at these resources are maximised. These schedules maximise capacity utilisation and, therefore, control material flow throughout the whole manufacturing system. Within CBC systems Vollum, (1988), identified that continuous efforts should be made to reduce batch sizes through reducing set-up times, improving quality and improving equipment reliability. These efforts should be normally performed as part of a wider continuous improvement philosophy and receive focus through being directed at improving levels of capacity at constraint resources. Several variations of CBC systems exist, i.e. Buffer Management, (Goldman and Boddy, 1997) Optimised Production Technology (OPT) (Goldratt, 1980), Theory of Constraints (TOC), (Goldratt and Cox, 1984), and the Drum-Buffer-Rope (DBR) technique (Goldratt and Fox 1986).

2.3.9.1 Optimised Production Technology (OPT)

The Optimised Production Technology (OPT), manufacturing control philosophy was developed by Goldratt, (Goldratt 1980), to provide planning and scheduling facilities for batch manufacturing environments. OPT attempts to generate effective schedules using the basic rules listed in Table 2.5. These rules are primarily used to generate schedules that enable shop floor resources to contribute towards maximising throughput and inventory and minimising operating expenses. At the root of these OPT rules, is the need to focus on planning and optimisation of the constraint or bottleneck resources as shown directly through use of rules 2, 4, 5, 6 and 9 and indirectly through the use of the remaining rules, i.e. 1, 3, 7 and 8.

Table 2.5: Rules of OPT (Goldratt, 1980).

1. Balance flow not capacity. 2. Let bottlenecks determine the use of the non-bottlenecks and do not seek machine utilisation. If a resource is activated when output cannot get through the constraint, then all it produces is inventory. 3. Utilisation and activation of a resource is not the same thing. Activation is when a resource is working but utilisation is when it is working and doing useful work. Producing stock for inventory is not useful work. 4. An hour lost at a bottleneck is an hour lost in the whole system and cannot be recovered. 5. An hour saved at a non-bottleneck is a mirage. 6. Bottlenecks govern both throughput and inventory. 7. A transfer batch is not necessarily equal to a process batch. If you break down the process batch into smaller batches the flow will be increased. 8. Process batches should be variable and not fixed. 9. Schedules should be established by looking at all the constraints simultaneously. Lead times are

The underlying foundation of OPT is, therefore, constraint management with the principal objective being to establish a process of continuous improvement through synchronised manufacturing. Here OPT defines ‘synchronised manufacturing’ as a systematic method of moving material quickly and smoothly through the production resources of a manufacturing facility in response to market demand. The limitations of OPT in promoting synchronous flow has been identified by Matsuura et al. (1995), these are, i.e.:

a. existing complex and costly data processing systems may need to be replaced,
b. management styles may need to change,
c. repositioning of equipment on the shop floor may be necessary,

d. cost and accounting systems may need changing,

e. retraining of employees may be necessary, and

f. the schedules produced by OPT must be followed explicitly.

2.3.9.2 The Theory of Constraints (TOC)

The Theory of Constraints (TOC) is an operations planning and control philosophy that evolved from OPT, (Goldratt 1988), and shares the same basic aims of OPT in terms of maximising throughput through constraint resources and minimising non-value added activities. In addition, both TOC and OPT are based on the assumption that individual production systems must have at least one constraint since if a constraint did not exist then the system would make unlimited profit. A constraint is, therefore, "anything that limits the system from achieving a higher performance". However, TOC adopts an alternative approach, compared with OPT, to the achievement of these aims. In this respect the basic rules of OPT have been replaced by the five steps shown in the Table 2.6.

Table 2.6: Focusing Steps of TOC

1. Identify the systems constraints
2. Decide how to exploit the systems constraints
3. Subordinate everything else to the above decision
4. Elevate the systems constraints
5. If in any of the previous steps a constraint is broken, return to Step 1. Do not let inertia become the next constraint.

These steps provide a means for focusing on continuous improvement activities, (Rahman 1998), as the TOC philosophy professes that the existence of constraints represents opportunities for improvement. Here constraints are viewed as positive elements, that determine the performance of a system, and hence a gradual improvement of the systems constraints should improve overall system performance.

There are distinct advantages with using TOC, rather than MRP, in terms of aiding synchronous flow, i.e.:

a. MRP treats individual manufacturing processes as isolated sets of events, whilst TOC adopts a project management approach by considering the flow of material between process, and
b. MRP considers parameters, such as process times and lead times, to be deterministic in nature whilst TOC takes a more realistic approach in treating them as stochastic variables.

Table 2.7 provides a comparison between the characteristics of MRP and TOC in terms of their ability to promote synchronous flow, (Umble and Srikanth, 1990) (Wild, 1984) (Goldratt 1980).

Table 2.7: Comparison of MRP and TOC

Requirements for synchronous flow	**MRP**	**TOC**
Pull system, production is authorised as inventory is consumed	Push system, schedules of what should be started in production based on demand	Pull/push system
Small batch sizes	Netting, subtract on-hand inventory and scheduled receipts from the gross requirements	Batch sizes are specified for each operation.
Rate based schedule	Batch sizing, divides the netted demand into batch sizes to form jobs	Bottleneck resources are not overloaded
Reliable processes, Process capable, Flexible labour	Time phasing, off-sets due dates with lead times to determine start times	Critical resources are optimised
Responsive maintenance, planned maintenance	BOM explosion, provides an hierarchical parts list for each finished product	Events planned for the future are considered i.e. planned maintenance.
Balanced cycle across process operations (Takt-times), Kanban	Forecasting, together with known orders provide an anticipated schedule of finished products.	Flow of products are synchronised through each resource.
Short set-up times	Safety stocks, to protect against inaccurate forecasts	Existing set-ups at each machine are considered.
Product dependant process, Dedicated work stations		The correct product mix is maintained.

From the table it can be seen that both MRP and TOC have certain commonalities that allow them to be combined to complement each other, i.e. (i) MRP is used to schedule and order materials, (ii) the planning system employs a modified MRP system, which consists of an aggregate production plan, a stable master production schedule (MPS) and a bill of materials for each product, (iii) TOC provides a set of time-phased shop orders, (iv) the capacity requirements plan and the rough-cut capacity are fed from the capacity analysis carried-out on the shop floor using TOC, (iv) the MPS is driven, not by customer orders, but by the capacity constrained resources.

2.3.9.3 Buffer Management

Buffer management, (BM), has been developed to deal with the complexity involved in scheduled job shops by focusing attention on specific critical resources. Gardiner et al (Gardiner et al 1993) identified the BM abilities, Table 2.8, of buffer management.

Table 2.8: Abilities of Buffer Management

a. provides a framework that reduces the complexities of material flow into an understandable format,
b. reduces drastically the number of resources that must be explicitly scheduled,
c. warns of potential disruption to the production plan,
d. controls lead time, i.e. lead times at calculated from the bottleneck processes output.
e. guides continuous improvement methods,
f. offers a significantly improved alternative to the kanban production system,
g. aligns local resource performance measures with organisational performance, and
h. makes traditional job shop capacity management techniques obsolete.

These abilities enhance synchronous flow in that they reduce the complexity that restricts flow, i.e. the processes are scheduled only to the bottlenecks needs. In addition, the requirements for flow, listed in Table 1.2, and strategically placed managed buffer inventories allow production to continue during disruptions to the system.

2.3.9.4 Drum-Buffer-Rope System (DBR)

The technique of Drum-Buffer-Rope (DBR) evolved, (Goldratt and Fox, 1986), as a means of providing planning and control, within manufacturing systems managed using the TOC approach, in order to provide a more complete planning and control system that protects throughput. The DBR system is a finite scheduling mechanism which is an improvement to the TOC philosophy which merely balances material flow within production systems, (Goldratt and Cox 1984). DBR, therefore, protects a HV/LV manufacturing system from the possible failure mechanisms that may exist but is limited, (Umble and Srikanth 1990), due to:

a. failure to identify the correct bottleneck and/or CCR resources and/or recognise when bottleneck/CCR changes take place due to changes in product demand,
b. failure to provide flexible labour that can move between constraints and non-constraints,
c. presence of large amounts of disruptive process variance, (e.g. rework, breakdowns), causing those processes that represent constraints to quickly change,
d. failure to develop adequate schedules that maximise throughput at the bottleneck and/or failure to provide responsive rescheduling that can cope with bottleneck changes,
e. failure to manage capacity of non-bottlenecks, and
f. failure to calculate buffer quantities correctly.

DBR controls the flow of material through a manufacturing system in order to produce products in accordance with market demand with a minimum of manufacturing lead-time, inventory and operating expenses. The three main DBR components, (Umble and Srikanth 1990), are:

i. The ‘Drum’ which sets the throughput pace of the whole system, i.e. to that of the slowest operation.
ii. The ‘Buffer’ which is the time provided for parts to reach the ‘protected’ areas, such as the inventory before the bottleneck.
iii. The ‘Rope’ which links the bottleneck with the entry work centres, i.e. work centre schedules.

Using a combination of scheduling and buffer management DBR protects a system and its processes against the effects of variability by explicitly exploiting constraint resources, (Duclos and Spencer, 1995). In this respect, because DBR buffers the effects of variability it is assumed able to successfully operate at high levels of variability.

The DBR system appears, therefore, to be a potential method of co-ordinating continuous improvement activities and determining time scales, and resources, i.e. (i) DBR can be a push, pull system or a highbred combination of both, (ii) DBR enables improved synchronisation of manufacturing activities within a high variety, low volume batch manufacturing environment by scheduling only to the bottlenecks needs, (iii) it enables reduced inventory, reduced lead time, and maximum throughput to be achieved. DBR, therefore, provides a framework for the planning of CI activities in terms of identifying the priorities of CI activities that need undertaking and their sequence, (Duclos and Spencer, 1995).

DBRs finite scheduling system is capable of controlling high variability of component parts, and variable demand equally as well as medium to high volume environments, (Umble and Srikanth 1990), by reducing the complexities that are involved in controlling material flow through use of buffer management and scheduling of CCRs to enable optimum throughput, in terms of promoting synchronous flow within HV/LV environments.

2.4 Lean Practices & Standardization

Toyoda, (Toyoda 1988), and Shingo (Shingo 1989) developed a disciplined process focused lean production system, i.e. the Toyota Production System, the aim of which was to minimise the use of resources that did not add customer based value to a product.

The removal of non added value work with a Toyota Production System-based manufacturing system, which is achieved through the elimination of the seven wastes, is essential to achieving flow manufacturing since these wastes act as barriers that interrupt synchronous flow, i.e. the seven wastes are, (Ohno, 1988).

i) Waste from producing defects, rework, and rejects, including unnecessary inspection, ‘not right first time’ and change-over scrap.

ii) Waste in inter-process transportation, and in-process materials handling including double handling.

iii) Waste from inventory, stores, buffers, use of excessive processing, and batch sizes.

iv) Waste from overproduction, producing parts too early, too much, just-in-case.

v) Waste in waiting time, materials queuing, un-scheduled stoppages, people not productively employed, expediting.

vi) Waste in processing, too fast, too big, too variable, i.e. matching machine capacity to the process requirements.

vii) Waste in motion, reaching, bending, exertion, excess walking, i.e. excessive unnecessary movement that adds time to a process (Nicholas 1998).

According to Ohno, (1988), every activity that takes place in a manufacturing system should add value to the system output. The value-added approach classifies activities as either value-added or non value-added, and with the latter, the absolute necessary activities are identified, and all other activities are candidates for elimination where the aim is to minimise non-value added activities and maximise added-value activities. Although in large manufacturing organisations it has been found, (Gunasekaranet al. 2000), difficult to run efficiently without such service-based activities as purchasing and production control, the aim is to eliminate all unnecessary activities within these functions. The involvement of unnecessary non added-value tasks during production affects the flow, or is involved as a result of poor flow, (Shingo, 1989).

Standard operating procedures (SOP) are an essential element of the Toyota lean manufacturing philosophy, and are used to completely define all aspects of a task, operation, or process within an organisation. They are an essential element to synchronous manufacturing, as they provide the planners and schedulers with accurate and up-to-date information about cycle time and operations capacity, (Bicheno 2000).

In terms of promoting synchronous flow within HV/LV, SOPs are essential, as high variety production can be more complex and variable which requires the need for standardised working procedures to reduce variability in production times and set-up times which have a greater affect when involved with low volumes, (Stockton and Lindley 1995). The reduction of variability in production tasks enables increased accuracy of the buffer sizes within DBR (Khalil et al. 2006), which are designed to promote the optimum flow of material with a minimum amount of inventory. It is important, therefore, to keep inventory low as a high variety of parts within a low volume environment can be costly if demand changes or if there is a design change.

MRP, MRPII and ERP are still the most common form of operating system used for complex manufacturing, although lean tools and techniques have been implemented to reduce waste in an attempt to reduce costs, but the literature review has shown that MRP system data output is normally out of date and unreliable for synchronous flow planning purposes (Stockton and Lindley, 1995), (Muhlemann et al. 1993).

JIT/Toyota Production System has been proved to be effective in promoting flow whilst eliminating waste and highlighting quality issues, but often fails in Western countries due to general misconceptions and the fact that there must be a base operating methodology already in place that can effectively utilise the lean tools and techniques of the Toyota Production System.

The Literature has also identified that DBR methodology has an inherent lean framework that is able to highlight areas that require concentration of CI efforts that will synchronise processes and improve throughput whilst reducing waste. Table 2.7:

Comparison of MRP and TOC details how each methodology accommodates synchronous flow and that MRP could be enhanced if TOC was integrated into areas of MRP. TOC has also been identified by the literature as having the greatest benefit to high variety low volume production requirements and previous research by Duclos and Spencer (1995), Lambrecht and Segaert (1990), Sale and Inman (2003) and Chakravorty and Atwater (1996) who have identified that TOC/DBR out performs other systems when there is high variety and low volume manufacturing, but this changes and is shown in there results, when higher volumes and less variety is manufactured.

Most of all the literature has highlighted the benefits of material flow through a manufacturing system and the techniques for achieving it, and that the TOC methodology is designed to improve flow and identify the constraints that impede flow where continuous improvement techniques can be focused to break the constraints (Umble and Srikanth, 1990). Therefore DBR/TOC has the best potential for promoting flow in HVLV environments, not forgetting that these critical chain techniques have been used for project management, hence HVLV, long before it became a manufacturing methodology.

Chapter 3 - Drum-Buffer-Rope Methodology

3.1 Introduction

Chapter 2 examined the alternative methods available for controlling materials within high variety/low volume manufacturing environments and identified the Drum-Buffer-Rope (DBR) mechanism as of greatest potential value. DBR, (Goldratt and Fox 1986), is a finite scheduling mechanism that aims to balance the flow of materials through production systems such that products can be produced in accordance with market demand using minimum resources. The basic operational components of DBR are;

a) The drum provides the master production schedule that is consistent with the requirements and capabilities of the plant, i.e. sets the throughput pace for the whole system.
b) The buffer is the time provided for parts to reach the protected areas. The protected areas are the Drum, the due dates and the assemblies of constraint parts with non-constraint parts.
c) The Rope is a schedule for releasing raw materials to the shop floor and is derived according to the Drum and Buffers, i.e. links the bottleneck with the entry work centres.

Below figure 3.1, is a diagram of a typical system which is compiled from various sources, to demonstrate the positions of the controlling elements of DBR that are described in this text.

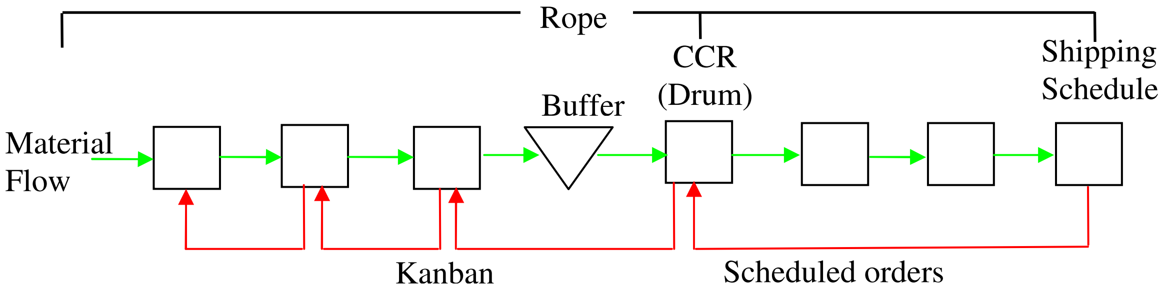

Figure 3.1: Example of a method of DBR control system.

This chapter provides a detailed analysis of each of the above components and their roles within the overall DBR process. The chapter provides critical analysis of the research literature which identifies the benefits and limitations of using DBR within manufacturing.

3.2 DBR Overview

Drum-buffer-rope (DBR) is essentially an operations planning methodology that schedules the flow of material through a manufacturing system where the aim is that products should be produced in accordance with market demand using where possible minimum lead-times, inventory and operating expenses. Seeking to achieve these aims, it concentrates on managing the flow of products through the system such that they meet the needs within the system of the bottleneck process. Since the bottleneck process controls the level of system throughput through a manufacturing system then managing this resource's throughput effectively manages the system's overall throughput. If no clear bottleneck process exists, then the DBR process attempts to focus on one or more of the capacity constrained resources (CCR).

There are similarities between DBR and MRP/MRPII systems in that a DBR system uses a scheduled release of products to control the production rate, and a safety stock or buffer at the bottleneck to guard against those stoppages that may be caused by material shortages through lack of materials arriving from upstream workstations. The focus of DBR on the bottleneck is perhaps the main difference between the two systems, since MRP plans are created independently from constraints on production and material plans, and production plans are based on lead times within the supply chain. Hence, a frequent problem caused by the use of MRP-based approaches, is the overloading of operations which result in a schedule that requires more production capacity than is available, therefore, increasing WIP inventory. However, when using the TOC-based DBR approach the capacity constraints are reflected in the schedule and are determined by the capacity that is available, (Nicholas 1998).

According to Umble and Srinkanth (1990), the DBR system facilitates synchronous manufacturing by:

a) enabling a manufacturing system to execute its planned product flow during a specific planning period, and
b) managing the results of deviations to the planned product flow caused by variability within the system.

Goldratt (1988) identified the basic sequence of tasks required to implement a DBR planning methodology, i.e.:

i) Identify the bottlenecks and capacity constrained resources (CCRs).

ii) Schedule the bottleneck or CCR such that maximum use is made of its available capacity.

iii) Synchronise production at all other resources to the production schedule at the bottleneck or CCR.

iv) Identify the pre-process locations where buffer inventory needs to be held.

v) Quantify the amount of buffer inventory that should be held at each of these locations such that there is adequate protection from disruptions, but minimal excess inventory.

In terms of mixed-model flow processing manufacturing systems, DBR assumes that within these, there are a small number of processes with scarce resources, i.e. CCRs that determine a system's level of throughput. DBR attempts to ensure that maximum system output is obtained at these processes by protecting their throughput, i.e. methods must be used to ensure maximum utilisation of CCR resources. For example, delays in delivering materials to the constraint resource need to be prevented since these may result in under-utilisation of the CCR through lack of work. In mixed-model manufacturing systems each of the tasks required to fully implement DBR control becomes increasingly difficult as the levels of product and process variability increases. The essential reason for this is that the process that represents the CCR often changes, sometimes on a weekly basis, i.e. if product mixes change then so may the capacity requirements for individual processes and hence that process with least spare capacity could also change.

In order to assist in identifying the CCR, and therefore facilitate the use of the DBR control approach, it is necessary to initially generate:

a) accurate process mappings of the material flows through the manufacturing system for each individual product,
b) estimates of the duration times for processing tasks involved, i.e. times per part at each resource and items of processing equipment, and
c) estimates of set-up times at the bottleneck and CCR.

3.2.1 Identifying the Bottleneck and / or Capacity Constraint Resource (CCR)

Within a DBR planning environment the type of resource, in terms of its available capacity, determines how it is treated during the DBR planning process. Here Goldratt and Fox (1986) identify the four basic types of resources as those listed in Table 3.1.

Table 3.1: Types of Resources and DBR Planning Responses

	Bottleneck	**Non-bottleneck**
CCR	Will constrain actual flow, both in quantity and time. Must be considered in planning the product flow.	Will constrain the timing of the actual flow, but not the quantity. Must be considered in planning the product flow.
Non CCR	May constrain actual flow, both in quantity and time. Need not be considered in planning the product flow.	Does not constrain the flow, either in quantity or timing. Need not be considered in planning the product flow.

3.2.1.1 Identifying Bottleneck and CCR Processes

Traditionally bottleneck resources have been identified simply by visiting the shop floor and visually identifying one of the following:

i. the process that had the largest pre-process queue of jobs awaiting processing,
ii. the process servicing those jobs with the highest capacity requirements,
iii. the process where jobs had the longest waiting time before they were processed,
iv. the process that possessed the longest job cycle time.

However, selecting one of these approaches is a simplistic approach, since in practice the bottleneck may not necessarily be the slowest operation, or the operation with the least capacity, but may result from a combination of these factors or less obvious reasons such as high job arrival rates. Hence, in high variety/low volume manufacturing environments identifying the actual bottleneck resource can be difficult since it can result from combinations of the reasons described above.

Capacity constrained resources (CCRs) differ from the CCR-bottleneck process in that they normally possess more capacity than needed to process the jobs allocated to them. However, the jobs to be processed on CCRs normally must be carefully sequenced such that capacity is not lost through schedule-created idle time, for example, when excessive set-ups are carried out or the process lies idle awaiting work, or the process is prevented from moving current work away from the processing area and therefore is prevented from receiving and processing the next job. If scheduling is not effective in avoiding such situations occurring, then such processes may become bottlenecks.

3.2.2 Scheduling the Bottleneck Resource

The primary aim of the scheduling function within a DBR system is to ensure that the bottleneck resource where possible is fully activated, i.e. employed in processing, and adding value to customers orders. Achieving this aim removes the main constraint from enabling the overall production system to achieve its maximum throughput volumes. However, in order to maximise customer service levels the jobs processed by the bottleneck resource should only be those that are required by customers. Hence, as in figure 3.2 below, as customer orders are received they are used to generate appropriate works orders and these works orders are sent directly to the bottleneck resource to inform the scheduling process. The resulting schedule should then, for the bottleneck be able to determine the sequence in which these work orders, such that customer order due dates are achieved and throughput levels are maximised (Goldratt and Fox 1986).

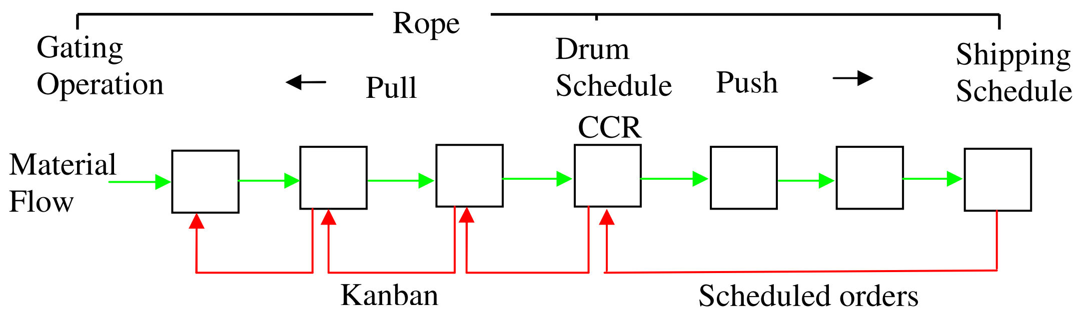

Figure 3.2: Example of DBR Bottleneck/CCR scheduling

Atwater and Chakravorty (2002) who studied the utilisation of CCRs in DBR systems using simulation identified that "one of the reasons that DBR type systems are so appealing is the approach they take to finite loading of orders into the schedule". Here DBR develops detailed schedules for all processes within the manufacturing system, but only DBRs 'finite capacity' loads the system's recognised bottleneck.

By focusing on scheduling the bottleneck process, the complexity involved in scheduling multiple processes is avoided, i.e. the bottleneck process is scheduled and then this schedule is propagated to non-bottleneck processes.

Variability within manufacturing systems normally results in delays in the scheduled completion times of jobs at up-stream processes and hence prevents the schedule adherence of down-stream processes which may include the bottleneck. Buffer stocks are used to protect the bottleneck against fluctuations occurring at non-bottleneck operations (Umble and Srinkanth 1996). These buffers ensure that the requisite materials are available for each customer order prior to production starting at the bottleneck, i.e. resource buffers are therefore established before the bottleneck process. Buffer stocks are held at critical points in the system, i.e.

i. The 'shipping buffer' is defined as a liberal estimation of the manufacturing lead-time from the CCR to the completion of an order. If a CCR is not involved in the chain, i.e. the process is not internally constrained, then, the shipping buffer is the lead-time from the release of raw material to order completion.

ii. The 'CCR buffer' is a liberal estimation of the manufacturing lead time from the release of raw materials to the site of the CCR and includes the time required to move WIP from raw material release to the point in time when it is placed in the pre-process CCR buffer awaiting process.

iii. The ‘assembly buffer’ is a liberal estimation of the manufacturing lead-time from the release of raw materials to the point in time when it is placed in the assembly process buffer where the CCR parts and non-CCR parts are combined (Schragenheim and Dettmer 2000).

3.2.3 Synchronising Non-bottleneck and CCR Resources to the Bottleneck

The “drum” provides a master production schedule for the bottleneck process that is used to set throughput rates for all other resources within the system, by communicating throughout the plant the processing requirements that are necessary by all other resources to support the bottleneck’s master production schedule. The drum, therefore, acts to restrict the throughput of all non-bottleneck processes to provide only for the needs of the bottleneck process. This prevents more jobs being released into the system than the bottleneck throughput capacity could process, hence, preventing build up of WIP inventory from arising in front of the bottleneck. The bottleneck’s need for input materials, therefore, provides all other schedules used within the system. Hence, this reduces the scheduling complexity since only a relatively few critical processes must be carefully managed using schedules in order to control the entire system successfully. These are ‘material entry points’, ‘capacity constrained processes’, ‘divergent processes’ such as disassembly areas, ‘convergent processes’ such as assembly areas and ‘bottleneck’ processes. It is the release of time-phased schedules to these areas that ensure that non-bottleneck production is matched to bottleneck production (Umble and

Srikanth1995). The use of the Rope mechanism, i.e. the schedule for releasing materials into the system to the rate of the 'Drum' (bottleneck or CCR) operation, also reduces the problem of communicating the master production schedule requirements to the non-schedule release points since these work centres may now be controlled by the use of simple priority sequencing rules such as first in, first out (Umble and Srikanth 1990), i.e. schedules hence, need not be issued to non-CCR operations.

There are various methods of synchronising a DBR system, Hopp and Spearman (1996), described a method of synchronising the resources to the CCR using a modified 'CONWIP' control process, i.e. Constant Work in Progress, where signals are sent from the CCR bottleneck to the material entry stage of a manufacturing system rather than in a traditional 'CONWIP' where signals are sent from the completed order exit stage to the material entry stage.

From the perspective of developing effective production schedules, the critical constraints in a manufacturing plant are driven by market demand, capacity, and material limitations. To determine the basic production plan these constraints are normally considered as follows, i.e.:

a. the planned production quantities are set such that these quantities do not exceed projected market demand,
b. sufficient supply of materials are made available to support the planned production, and
c. the proposed product flow required to support the planned production is set such that overloading of the processing capabilities of resources does not occur.

The above rules help enable master production schedules to be developed that greatly improve the quality of the resulting production plan. The specific metrics used to measure the quality of any manufacturing system plan is; throughput, operating expenses and inventory.

3.2.4 Identify the Location of the Buffers

As previously highlighted in paragraph 3.2.2, in order to prevent disruptions to scheduled throughput and hence missed delivery dates, specific types of processes within DBR systems must be prevented from lying idle using buffer stocks due to the effects of up-stream product and process variability. Here, (Duclos and Spencer 1995), used simulation models of the operation of MRP and DBR for a complex production environment to study the effects of strategically placed buffers in a "T" logical structure, i.e. a flow shop. Their study indicated that such buffers within DBR systems produced significantly improved throughput and delivery performance results than the use of MRP methods.

(Lambrecht and Segaert 1990); identified DBR as a "*long pull"* system because a fixed level of inventory is maintained in the system, with the materials to produce one item being pulled into the system as a completed item exits, i.e. as items are delivered to customers. A comparison was made between DBR and a Kanban system (Raban and Nagel 1991), where each operation possessed low levels of inventory, fixed maximum buffer quantities (fixed inventory), and where production was pulled between operations. Results indicated that small fixed buffers provided less protection from product and process variability upstream of the constraint and hence resulted in greater numbers of late shipments and levels of lost output.

As DBR uses inventory to buffer the effects of variability it is assumed by Schragenheim and Dettmer (2000) to be able to operate at high levels of variability. Their research indicated that a buffering approach is an effective method for improving throughput and flow of materials within a manufacturing system. In this respect, further research was carried out comparing the downtime, process time and inventory variability between these approaches within DBR, i.e.

a. A survey-based comparison of performance and change in performance of organisations using an MRP manufacturing line balancing approach against, JIT and TOC/DBR approaches (Sale and Inman 2003).
b. A balanced line, JIT and DBR approach was simulated for comparison. (Chakravorty and Atwater 1996).

The results of this research overall found that DBR out performs other methods in the main areas such as throughput, inventory and costs where operational performance is measured. In particular DBR was found to be more effective for maximising throughput of systems with high levels of product variety and low production volumes.

The proficient use of buffers can, therefore provide, high levels of throughput protection for moderately small levels of work-in-progress inventory. Using both schedules and buffers, DBR protects a system and its processes against the effects of variability by explicitly exploiting constraint resources (Schragenheim and Dettmer 2000).

3.2.5 Quantifying and Managing the Buffer Size

Hence buffer sizes must be carefully managed in order to prevent such disruptions occurring, i.e. the minimum quantity of inventory in these buffers must be carefully determined. In addition, their maximum quantity must also be managed such that excessive additional production lead times do not result and excessive inventory costs are incurred.

There have been various techniques devised for determining the size of a CCR buffer in a DBR system Srikanth and Umble (1997). Tu and Li (1998) for example, used a trial and error approach that consisted of first determining an initial buffer size by simply using experience or past practice. These initial buffer sizes are then monitored and adjusted through a process known as buffer management, i.e. a method of setting and controlling the levels of inventory held before a CCR.

Buffer Management is used as a signal of potential disruptions to the production plan, and when to take action to expedite material to avoid this disruption. The Buffer is divided into three regions as in Figure 3.3., if material has not arrived when a third of the buffer has passed, (a hole in region 2) material should be found and potential obstacles removed. If two thirds of the buffer has passed without receiving material, (hole in region 1) then expediting should take place to avoid disruptions to the production plan. The buffer size is deemed to be correct if 90% of production is achieved without the need for expediting, less than this indicates the requirements of a larger buffer, if expediting is rare, then a smaller buffer is necessary (Gardiner et al.1992).

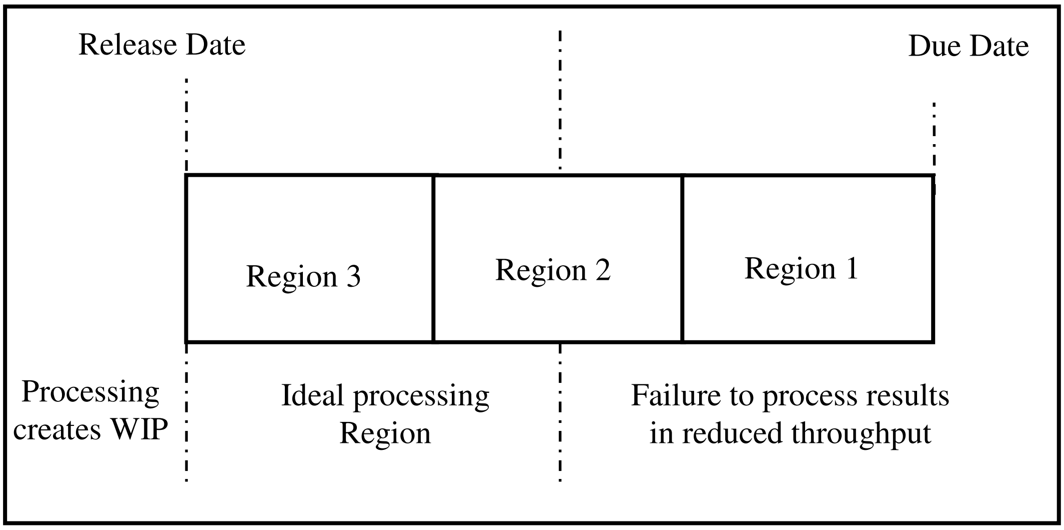

Figure 3.3: Buffer with related performance measures

Figure 3.3 details that if,

Region 3 is empty- take action to find material.

Region 2 is empty- take action to expedite material to maintain the production plan.

Goldratt (1990) suggested determining initial buffer sizes by estimating the current average lead time of all tasks sequentially linked to a specific buffer, and dividing this lead time by five. Srikanth and Umble (1997) suggested that the total buffer for a specific product should be approximately half of the company's current manufacturing lead time, where as Schragenheim and Ronen (1990) suggested a constraint buffer size of three times the minimum cumulative processing time to the constraint.

The limitations of estimating the initial safety buffer size and then monitoring to achieve the optimal size is; if production is more complex i.e. product mix is high with varying demand, the bottleneck may quickly change to another position before the optimal buffer is found so these techniques are assuming fairly low variability in production, and using estimating techniques such as the 50% rule for safety buffers results in serious overestimating (Herroelen and Leus 2007).

Other techniques include computer simulation studies, for example Tu and Li (1998) developed a ‘constraint time buffer’ determination model by using a tree structure to represent the relationship between a constraint process and its upstream ‘feeding’ processes. This was carried out by calculating the mean time between failures (MTBF) of each of the upstream processes. A mathematical relationship between the output of the up stream feeder processes, the CCR schedule and the process time of the CCR was then formulated and used to determine the constraint buffer size. This model accounted for variability caused by machine breakdowns, but did not take into account other sources of variability such as variability in processing times and variability in the sizes of transfer batches moved between processes.

A queuing analysis approach to estimating time buffers Radovilsky (1998) was devised by modelling the constraint resource as an M/M/1/K system,

A queue is described in shorthand notation A/B/C first devised by Kendall (1953)

A = the distribution of inter-arrival times,

B = time between completion,

C = number of servers.

Where:
M = Poisson process (random).
M = Service time is exponentially distributed.
1 = There is one server (1).
K = There is a limit to number in the queue.

Therefore, the optimal number of units waiting in the queue in front of the constraint, i.e. optimal size of time buffer, is determined, based on maintaining the maximum operational profits whilst protecting the constraint from becoming idle. Practical restrictions to the use of this approach are its assumptions that service times are exponentially distributed, Poisson's arrival times, hence Poisson's distributed arrival rates, when there is only a single server, i.e. the process within the system, in addition the model did not take into account the effects that disruptions at resources upstream from the constraint would have on arrivals at the constraint (Louw and Page 2004).

Louw and Page (2004) presented a more realistic approach using open queuing network analysis for estimating the size of the time buffers in TOC controlled flow lines. This work estimated the average flow time to the CCR buffer origin and the standard deviation of flow time. Using these two values together with an assumption of normally distributed flow times and a chosen service level, the final CCR buffer length is determined.

The output of this research produced a sufficiently accurate, quick initial estimate of the required time buffer sizes at the design stage of a production line. In developing the method, if the buffer lengths of CCRs are monitored in a timely manner there was less need to accurately estimate these buffer sizes.

These various approaches for estimating the initial buffer size before the CCR rely on buffer management to determine the optimal buffer size during production, estimating the buffer size by using assumptions or accumulative lead time before the CCR may result in excessive WIP if the bottleneck CCR were to quickly change to another location before the buffer management process becomes effective. In high variety manufacturing the CCR may have the tendency to change more frequently depending on product demand. Simulating the systems process as Tu and Li (1998) is a preferred approach as it can be applied easily when the CCR quickly changes, but their model may need to include other variables such as variability in transfer batches.

Yuan et al. (2003) presented a generic buffer management procedure that defines a method of monitoring the size and adjustment of the buffer. TOC buffer management uses a system that divides the buffer into three controlled zones, i.e. red, yellow and green with each zone representing one third of the total buffer. If the buffer drops into the green zone, no action is taken, if it drops into the yellow zone it signifies a warning and planning is necessary, but if it drops into the red zone immediate action must be taken. TOC claims that over a period of time the actions taken in response to the signals will eventually find the correct buffer size. The generic buffer management procedure developed by Yuan, Chang and Li (2003) uses just two buffer control zones, i.e. green for maximum buffer size and red for safety buffer size. The size of the buffer is again determined heuristically as with TOC, but this method claims to be more sensitive to variability due to the removal of the middle control zone, hence a greater level of monitoring is necessary to control the size of the buffer than the standard TOC method.

3.3 Summary of the Benefits and Limitations of DBR

Gardiner, et al. (1992) have documented the potential benefits of the DBR approach in terms of its ability to plan and control complex manufacturing systems, i.e.: DBR has been shown to;

a. provide the framework that simplifies the complexities of material flow into an understandable format,
b. reduce significantly the number of resources that must be explicitly scheduled,
c. warn of potential disruption to production plans,
d. control the lead time of individual customer orders,
e. identifies opportunities and directives for continuous improvement efforts,
f. offer a significantly improved alternative to Kanban pull production systems within HV/LV manufacturing environments,
g. align local resource performance measures with global organisational performance, KPIs and
h. make traditional job shop capacity management techniques less effective.

However, the presence of numerous sources of variability limits the effectiveness with which each of the tasks required to implement and operate DBR planning and control methods can be carried out. Since variability in product mixes demanded by customer can effect process and set-up times on machines they can hence lead to changes in the bottleneck resource. For example, as product mix variability levels increase, then bottleneck resources can be created at those processes that possess long cycle times or those that increasingly require long and/or frequent set-ups. The presents of high levels of variability therefore makes it difficult to consistently identify bottleneck resources. In addition, when planning and/or training cycles exceed the frequency with which bottlenecks change, then it may be impossible to use such techniques to provide sufficient flexibility to deal with these new bottlenecks.

In terms of bottleneck scheduling the following factors need to be determined, i.e. the sequence with which jobs need to be scheduled, the process batch size and the transfer batch size. Often, the sequence and/or values of these batch sizes may need to be re-determined each time demand levels and/or product mixes change. Because of this inability to locate bottleneck resources it is not always possible leading to materials arriving at bottlenecks late and, hence, reducing the buffer protection in the event of unexpected stoppages.

Several researchers Charney (1991); and Hopp and Spearman (2000), have highlighted that variation is an effect resulting from one or more underlying causes with (Hopp and Spearman 2000) classifying the basic types of variability occurring within manufacturing systems, including those using, DBR systems, as follows:

a. natural variability, i.e. variability in the basic batch cycle times required for an operator or item of processing equipment to complete a batch of components,
b. non pre-emptive outages, i.e. short stoppages that represent the variety of events, such as equipment change-overs and planned maintenance events, that cause minor stoppages within DBR operations, and

c. pre-emptive outages, i.e. long stoppages that represent the variety of events, such as major unscheduled equipment breakdowns, that cause major disruptions and stoppages in DBR operations.

Wild (1985); Muth and Alkaff (1987); and Blumenfeld, (1990) identified a wide range of these sources of variability which included demand and product type mixes, variability in equipment functioning and process operating capabilities, set-up times and reliability, operator absenteeism, operator abilities, motivation and skill levels, material and product quality, cycle times, delivery reliability of raw materials and components, and batch sizes both procured and produced. Schragenheim and Dettmer (2000) identified further causes of variation as absences, breakdowns, longer than expected set-ups and un-anticipated quality problems.

Further investigations by Chakravorty and Atwater (1996) were carried out when a balanced line, JIT and TOC/DBR approach was simulated for comparison, using Simulation Language for Alternative Modelling (SLAM). The results showed that at low levels of variation at a workstation JIT performs best if there is sufficient inventory, and at high levels of variation TOC/DBR performs best. The downtime results revealed that when station downtime is relatively high, TOC/DBR performs best, and when they are low, JIT performs best. The inventory results indicated that with low levels of inventory, TOC/DBR performs best with JIT and balanced lines performing equally as well as each other, but as the inventory level was incrementally increased, the JIT line improved until it out performed TOC/DBR with the balanced line trailing behind. The concluding results of these simulations revealed that TOC/DBR lines will significantly out produce both JIT and balanced lines at relatively low levels of system inventory, and also that TOC/DBR lines achieve there maximum output level with much lower levels of inventory in the system. JIT lines will significantly out produce TOC/DBR and balanced lines if there is sufficient inventory. In summary, each line was subjected to different combinations of variability in; downtime, process time and inventory levels, and their conclusions were as follows;

a. TOC/DBR lines will significantly out produce both JIT and balanced lines at relatively low levels of total system inventory,
b. TOC/DBR lines will achieve their maximum output level with much lower inventories in the system than JIT lines,
c. with sufficient inventory, the JIT line will significantly out produce both TOC/DBR and balanced lines,
d. TOC/DBR lines perform best when station variation is relatively high,
e. TOC/DBR lines do not perform as well as JIT lines when station variation is relatively low, and is the most heavily affected by changes in station variability,
f. TOC/DBR lines perform best when station down-time is relatively high, and
g. JIT lines perform best when station down-time is relatively low.

The existence of large numbers of potential sources and levels of variability is a major limiting factor to the successful use of the DBR method within high variety/low volume manufacturing environments. The ability to measure variability and its effects on an individual work area within a DBR whilst becoming increasingly essential to the effective design and operation of such systems can however be complex and time consuming. Knowledge of the levels of variability arising at individual work areas would assist during the design of a DBR system in allocating tasks to work areas such that utilisation may be improved. In addition during operation of the DBR system knowledge of variability effects would provide essential information in employing methods of dealing with variability to best effect. In this respect a number of strategies have emerged for dealing with the effects of variability within manufacturing operations, as set out by Khalil (2005) i.e.

a. through the balanced allocation of tasks to work areas,
b. effective sequencing of jobs into and through the DBR system,
c. adoption of an optimum mechanism for controlling material flows,
d. removing the causes of variation, e.g. through set-up reduction and total quality management activities,
e. reducing the levels of variation from individual causes, e.g. through lean-based waste reduction techniques,
f. combining sources of variation, i.e. through variability pooling and buffering, and
g. use of flexible resources to off-set the effects of variability.

Typically, having WIP inventory, increasing capacity, or increasing order lead-times has compensated for the problem of variation in environments with dependent resources.

3.3.1. Summary of DBR

The literature research revealed the following summary of TOC/DBRs benefits and limitations, i.e.

3.3.1.1. Benefits

a) Use of DBR provides focus for continuous improvement activities, i.e. identifying areas that would improve system throughput and areas that would merely create WIP.

b) DBRs ability to make use of both Kanban pull systems, and CONWIP systems allows greater scope for implementing lean practices.

c) DBR through its ability to make use of pull systems has the ability to be used as part of an MRP system.

d) DBR enables improved process synchronisation, when compared with JIT and MRP manufacturing activities, within a high variety, low volume batch manufacturing environment,

e) DBR enables simultaneous reduction in inventories and lead time as well as increases in throughput to be achieved, depending upon the level of variation in the system.

3.3.1.2 Limitations

a) DBR requires the determination of suitable buffer sizes at strategic locations within the system. Such locations can be difficult to accurately identify and their buffer sizes difficult to calculate. Such problems are more difficult when changes in the levels of input and output demand are frequent occurrences.

b) DBR requires the development of schedules and job sequences at strategic processes. Such schedules can be difficult to develop without reductions in the available processing capacity.

c) DBR depends on the accurate location of the systems bottleneck, incorrect identification of the capacity constrained bottleneck can result in increased WIP and decreased throughput.

d) DBR requires the use of flexible lead times when scheduling bottleneck resources since using fixed lead times can result in increased work-in-progress levels.

e) DBR requires estimation of bottleneck buffer sizes, since insufficient buffer sizes can result in bottle-neck starvation and consequentially system throughput. (Umble and Srikanth 1990).

f) DBR has limitations in terms of its ability to synchronise manufacturing activities, i.e. although the DBR method provides guidelines for locating buffers, it does not provide a procedure for quantifying a buffer size at the constrained resource bottleneck immediately, i.e. a slow reaction to change, but estimates and refines them during production using buffer management. Moreover, in plants with 'wandering' bottlenecks, this approach is often difficult to implement, here buffer management requires continuous monitoring and knowledge of changes in the bottleneck resource (Rodrigues 1994).

Although DBR has potential as a method of planning and scheduling low volume/high variety manufacturing systems, from its structure and philosophy, it can be seen to have limitations if the basic rules underlying the approach cannot be applied successfully. This can lead to the failure of DBR to operate at maximum performance, and the more complex the system the more likely failure will occur.

In general the benefits of using a Drum-Buffer-Rope system greatly out-weigh its limitations. However these limitations need to be resolved, and the intention of the current research is to resolve these current issues that are preventing the wider use of DBR systems by focusing on the following,

1. To identify bottlenecks, i.e. the accumulation of inventory before a process due to insufficient capacity.
2. Wandering bottlenecks, i.e. a change in bottleneck location due to demand or schedule change (the volatility of the system).
3. Inventory size, i.e. the work-in-process inventory for the whole system.
4. Time buffers, i.e. the fixed inventory before a process to enable continuous throughput during system variability.

Chapter 4 - Research Methodology and Experimental Design

4.1 Introduction

The aim of the current research is to establish the extent to which DBR techniques can be applied within HV/LV manufacturing environments.

Table 1.2: Limitations of Traditional Flow Process Systems (Khalil 1995) can also be interpreted as benefits and ideal requirements for process flow, as variability in general within the system is minimised and also enhanced by producing large batch sizes and thus fewer disruptions due to product changeovers. As described in chapter 2.2.4, it is generally recognised that high variety low volume environments whilst processing in batches causes disruption to process flow (Wild, 1984) and therefore a need to resolve the issues of poor material flow traditionally found within HV/LV manufacturing environments (Umble and Srikanth 1990).

The research objectives are to investigate the main elements of a DBR environment in order to generate a comprehensive description of the requirements for practical DBR implementation and operation and to attempt to improve the current limitations in using DBR, section 3.3, through use of simulation modelling. These requirements have been grouped into three areas, i.e.:

i. plant layout and kanban controls, i.e. individual workstations, variable process cycle times, push/pull manufacturing system.

ii. planning and control, such as scheduling, job sequences, inventory management.
iii. DBR infrastructure, such as inventory buffers, bottlenecks, variable workstation cycle times, bottleneck scheduling.

This chapter initially describes how an appropriate research methodology was adopted and the design of the experiments required by this methodology.

4.2 Selection of Research Methodology

The feasibility of using a range of qualitative and quantitative methods of data collection was examined during the research, i.e. existing case studies involving DBR systems within the research literature, actual observations of variable production environments, historical data from existing production systems, published historical data from various sources, surveys or questionnaires targeted at relevant manufacturing businesses within the UK, generating data via the use of a suitable modelling techniques such as discrete event simulation modelling.

A qualitative approach to the research was considered which would have involved use of methods such as, case studies, grounded theory, and narrative research. However using such methods the study would have been fundamentally interpretive in nature to the data drawing conclusions about its meaning personally and theoretically. Here, the researchers own thoughts and feelings, biases and interests may have been included in the qualitative research analysis and would only be able to look at the broader view rather than the detailed operations based analysis, required to achieve the research aims.

The literature review undertaken did not reveal the existence of detailed case study data of DBR systems that would be relevant for this study. This is probably due to limited use of DBR systems within industry, i.e. the required historical data was not available. The use of a quantitative research method was therefore considered with the use involving experiments chosen in preference to the use of surveys. Again, as with qualitative research; the use of surveys would not produce the depth of detail required to achieve the research aims.

Actual observation of a DBR system would have relied on the ability to gather data from specific industrial locations, and to accurately document the actual behaviour of its DBR system. This was not possible as there were no suitable DBR systems available for observation.

4.3 Data generation Methods

Generating data was therefore, considered the only appropriate method. This was achieved using discrete event simulation models which allowed:

i. The number of individual workstations within a model to be varied.
ii. A wide range of factors to be included in the model, such as set-up times, transfer batch sizes and sequencing of jobs.
iii. The ability to measure the effects of individual work stations, 'buffer levels' batch sizes and job schedules on system performance such as throughput.

Discrete event simulation models were compared for generating the data required to test the DBR optimisation processes developed; i.e.

i. Simquick, which is designed to carry-out process simulations using MS Excel spreadsheets, is capable of modelling simple processes such as waiting lines, inventory and supply chains, batch processes, job shops and processes with uncertain task times.

ii. Simul8 which is a commercial DES package in which simulations are time based and consider all interactions that exist between activities resources and constraints. The system also allows production randomness to be modelled enabling models to behave as actual systems would. It also produces output summaries of results that can be automatically exported to external packages for display and analysis. This package was selected due to its ability to model such random events.

4.4 Optimisation Method

4.4.1 The selection of an optimisation method

Optimisation software is often used to analyse the results of simulation experiments and optimise critical operational parameters. It has been widely used for optimising and improving systems in industry and research, and within manufacturing they have been successfully applied to problem areas, which include scheduling, Cleveland and Smith (1989) line balancing Minagawa and Kakazu (1992) and simulation. It also provides boundary controls for output statistics, linear constraints on the input options, and multiple stopping rules. Therefore, the use of an optimisation method would be a reliable tool for increasing the throughput whilst finding the optimal buffers for minimum inventory in a high variety manufacturing system.

GAs established by Holland (1975) has successfully been used to optimise various manufacturing planning problems. For example, Cleveland and Smith (1989) and Davis (1985) used genetic algorithms to schedule job shops, here Cleveland and Smith demonstrated the use of a GA on a range of scheduling problems. Stockton et al. (2005) used GAs to determine the minimum Takt time and the associated operator walk cycles at which a flexible manpower line (FML) can operate under a fixed number of operators. GAs were also used by Tenga et al (1988) to optimise the design of manufacturing systems, where the parameters examined included the length of conveyors, the work rate of robots, the size of buffer stocks and the number of pallets.

4.5 Experimental Design

The main methods of experimental design considered to generate the required data for analysis were:

i) Full factorial experiment action.

ii) Factorial design of experimentation.

Factorial experimental design was chosen instead of the full factorial 'one-factor-at-a-time' method. These are efficient at evaluating the effects and possible interactions of several factors (independent variables). The advantages of factorial designs over one-factor-at-a-time experiments are that they are more efficient and they allow interactions between variables to be detected.

The Taguchi method of using orthogonal arrays to reduce the number of experiments was selected due to its wide use in experimental scientific research and its ability to minimise the number of experiments needed, i.e. in this case discrete event simulation models.

4.5.1 DES Model Objectives

The DES Models developed needed to:

i) Model a DBR system in terms of the modelling elements listed in table 4.2.

ii) Allow the genetic algorithm to identify the process schedules that will maximise throughput using the minimum of buffer inventory in a variable demand environment.

iii) Allow alternative schedules to be modelled.

iv) Allow alternative product mixes to change the position of process.

Table 4.1: DES Modelling Elements

Bottlenecks
The ability to change product demand
Schedule
Buffers
DBR protected processes
Set-up times
Process Cycle times
Batches
Transfer batches
Machines capable of processing more than one part

In order to maximise throughput using minimum inventory, DES models must enable:

i) Identification of the capacity constrained bottleneck resource.

ii) Identification of the optimal buffer inventory level in front of the capacity constrained bottleneck resource.

iii) Identification of the maximum material throughput levels for a given set of schedules.

iv) Identification of the best transfer batch size that provides maximum throughput levels.

v) Identification of the best and optimum schedule for a given demand.

vi) Identification of the areas for continuous improvement.

4.6 Model and Simulation Design

The processes, material flows, and buffer locations that make up the basic model are shown in figure 4.1, and are detailed in table 4.2.

Parts A and B enter into a buffer before work station/centre 1 and parts B and C enter into a buffer before work station/centre 2, these could be also described as supply chain buffers. These parts are then machined by the relevant processes and then passed to their allocated buffers. The parts queue here until the schedule requires them or they are able to be processed. The assembly processes 3 and 4 can only work when all the mating parts are available. Work station/centre 5 is a dummy process which receives the finished products to schedule.

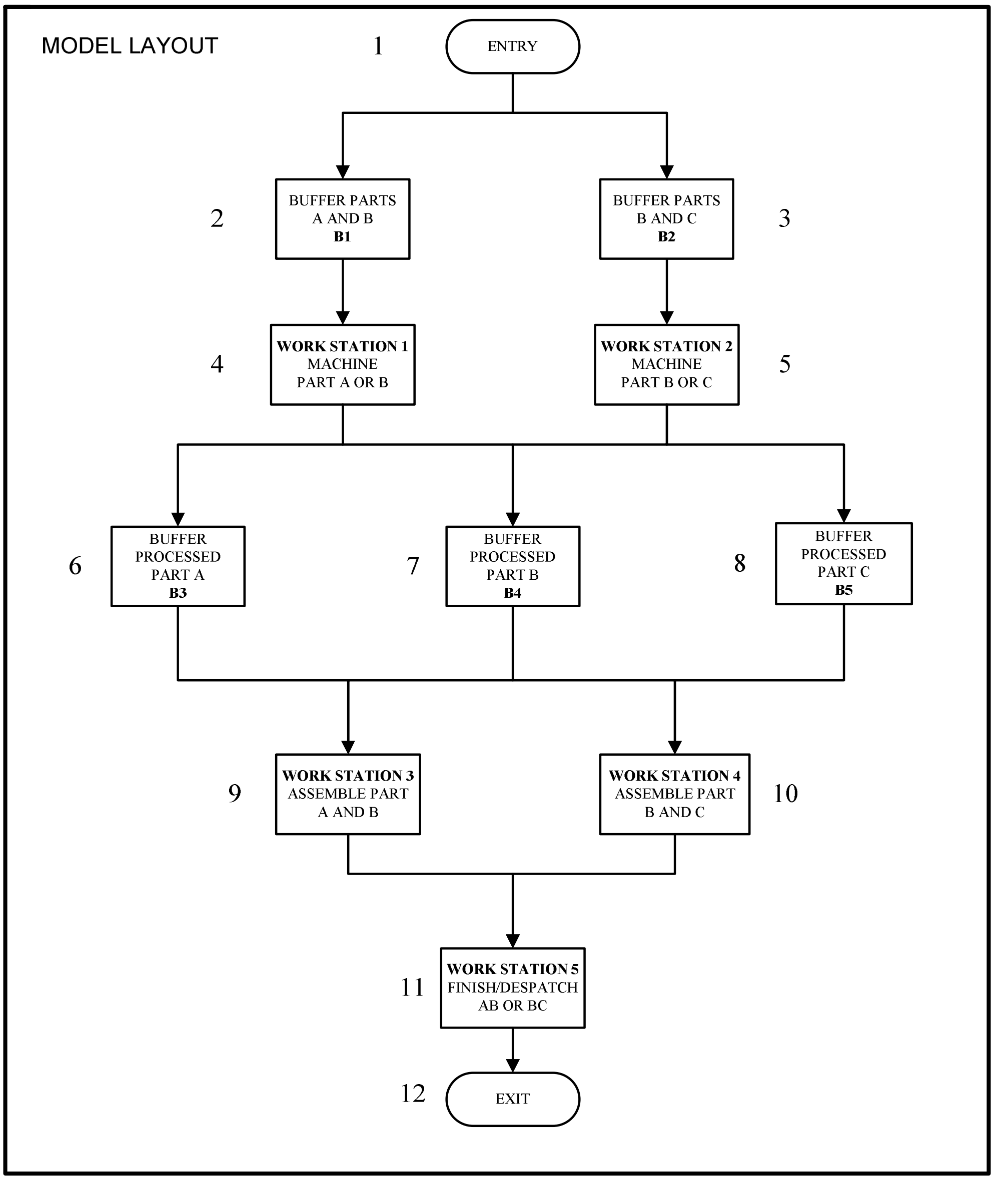

Figure 4.1: Model layout

The alternative values of model variables used within the experiments are listed in Table: 4.2.

Table 4.2: Model Elements and Values

Basic Model Elements and Parameters			
Model Constants	**Value (mins)**		
Run Time	20000		
Travel Time	0		
Model Elements	**Comments**		
1 Entry - No random numbers at entry.	Unlimited entry parts A, B, and C		
2 Holding Buffer – Processing parts A and B	Buffer levels at simulation start-up = 0		
3 Holding Buffer – Processing parts B and C	Buffer levels at simulation start-up = 0		
	Part	**Set-up Time (mins)**	**Cycle Time (mins)**
4 Machine 1 – Produces part A or B	A	30	2
	B	60	4
5 Machine 2 – Produces part B or C	B	60	4
	C	30	3
6 Assembly Buffer - Processed parts A	Buffer levels at simulation start-up = 0		
7 Assembly Buffer – Processed parts B	Buffer levels at simulation start-up = 0		
8 Assembly Buffer – Processed parts C	Buffer levels at simulation start-up = 0		
	Assembly	**Set-up Time(mins)**	**Cycle Time (mins)**
9 Assembly Process – Parts A and B	AB	0	6/unit
10 Assembly Process – Parts B and C	BC	0	7/unit
11 Demand –(dummy) AB or BC assemblies	As per schedule		
12 Exit	As per schedule		

Each experiment involved running a simulation 100 times to allow the optimisation process to find the best solution. All buffers were empty at the start of each simulation, and a warm-up period is not included. Travel times between work processes were set at zero.

The variables under the control of the optimisation process are:

Variables	Optimisation method
Pre-process buffer sizes	GA
Process batch sizes	GA
Process job sequences	Taguchi

The optimisation process will aim to:

Buffer Sizes	Minimise
Process batch sizes	Minimise
Process job sequences	Maximise

The performance measures used to asses the system efficiently are levels of throughput and levels of inventory, i.e.

i) The maximisation of system throughput.

ii) The reduction of WIP inventory and buffer stocks levels.

iii) The identification of the best schedule for a process batch using various transfer batch sizes.

The first set of experiments was carried-out using a 36 array which produced duplicate results, so a 16 array was then used which produced similar duplications from the sets of experiments (see appendix A and B) which then led to using the 8 array set of experiments.

Table 4.3: 8 Array Sequences of processes for Machine 1 and 2

Exp. Group	**AB AB BC**		*Exp. Group*	**AB BC BC**		**Transfer Batch Size for Each Experiment**			
	Order Sequence			Order Sequence					
	Mach/1	Mach/2		Mach/1	Mach/2	***TBS***	***TBS***	***TBS***	***TBS***
1	A	B	***5***	A	B	PBS		10	1
2	A	C	***6***	A	C		PBS	1	10
3	B	B	***7***	B	B	10	1	PBS	
4	B	C	***8***	B	C	1	10		PBS

TBS = Transfer batch size.

PBS = Transfer batch size = Process batch size.

There have been some assumptions causing weaknesses within the model that could be improved for further research, and they are as follows, cycle-times at the manual processes are fixed and there is no resource variability at these processes; set-up times are fixed and the model does not include break-downs as a source of variability. Another assumption is that material will always be available when required at the point of entry disregarding supply chain issues as this is not the focus of the research.

The final number of experiments to validate the research was able to be reduced by using the Taguchi array rather than duplicating lots of similar experiments and results which was an issue even when using the larger Taguchi arrays.

A basic DBR model was required to investigate these research needs and to refrain from straying from the DBR system methodology. A much more complex model was considered to be unnecessary at this stage of the research due to the volatility of a high variety DBR manufacturing system, and further research may include a more complex model to verify whether the same rules still apply under a more volatile system.

Chapter 5 - Results

5.0 Introduction

The aim of the first set of experiments was to determine if GA can find a new optimum solution after changes in product mix; initially experiments 1.4, 2.3, 3.2, 4.1 were undertaken to identify the conditions under which throughput is maximised for a product mix ratio of 3A, 2B, 1C; the results of these experiments are shown in Table 5.1.

The product mix ratio was then changed to 1A, 3B, 2C and experiments 5.4, 6.3, 7.2, 8.1 was undertaken to establish the new optimum conditions; again these results are shown in Table 5.1.

5.1 Results: Transfer Batch of 1

Table 5.1: Experiment Results: Optimal Buffer Size v Throughput

GA Optimal buffer size			TRANSFER BATCH OF 1				
EXP No.	**Total Buffer**	**Through Put**	**Buffer 1**	**Buffer 2**	**Buffer 3**	**Buffer 4**	**Buffer 5**
Exp 1.4	61	1262	24	22	14	7	18
Exp 2.3	43	1390	7	12	18	8	5
Exp 3.2	74	989	28	25	17	14	18
Exp 4.1	36	1380	5	10	17	5	4
Exp 5.4	82	1443	28	32	18	9	23
Exp 6.3	55	1818	7	15	23	10	7
Exp 7.2	94	1268	28	31	22	18	23
Exp 8.1	50	957	5	13	22	8	7
		Correlation =	-0.2473	-0.119	0.23078	-0.1766	-0.2017

A transfer batch of 1 has resulted with a low amount of buffer inventory in the system for all experiments.

Table 5.2: Experiment Results: Average Queuing Time v Throughput

Average queuing time			**TRANSFER BATCH OF 1**				
EXP No.	**Total Buffer**	**Through Put**	**Buffer 1**	**Buffer 2**	**Buffer 3**	**Buffer 4**	**Buffer 5**
Exp 1.4	61	1262	22.2	21.96	18	22.2	22.2
Exp 2.3	43	1390	21.32	14.54	21.46	18.77	27.32
Exp 3.2	74	989	26.78	34.54	33.9	19.09	27.64
Exp 4.1	36	1380	17.56	10.54	10.46	19.41	27.96
Exp 5.4	82	1443	36.43	36.54	42.5	22.39	30.94
Exp 6.3	55	1818	11.65	16.54	11.75	25.38	33.93
Exp 7.2	94	1268	33.21	25.54	40.18	24.91	33.46
Exp 8.1	50	957	9.54	8.54	4.9	22.09	30.64
		Correlation =	-0.0731	-0.0817	-0.0628	0.43433	0.34972

Apart from experiment 1.4, the difference between buffer 4 and buffer 5 average queuing times is exactly 8.55 minutes, but there is no strong correlation with average queuing time and throughput results for these experiments.

Table 5.3: Experiment Results: Minimum Queuing Time v Throughput

Minimum (non-zero) Queuing Time			**TRANSFER BATCH OF 1**				
EXP No.	**Total Buffer**	**Through Put**	**Buffer 1**	**Buffer 2**	**Buffer 3**	**Buffer 4**	**Buffer 5**
Exp 1.4	61	1262	28	24	10	14	26
Exp 2.3	43	1390	12	18	22	12	9
Exp 3.2	74	989	32	32	21	18	22
Exp 4.1	36	1380	8	14	19	9	8
Exp 5.4	82	1443	34	38	21	13	27
Exp 6.3	55	1818	14	18	26	14	11
Exp 7.2	94	1268	23	38	27	22	27
Exp 8.1	50	957	6	19	25	12	11
		Correlation =	-0.0988	-0.2074	0.13035	-0.2038	-0.2036

Schedule changes have more influence on the throughput than buffer queue times as there is no correlation with minimum queuing times; maximum queuing times revealed the same outcome and the chart Figure 5.1 visually shows this.

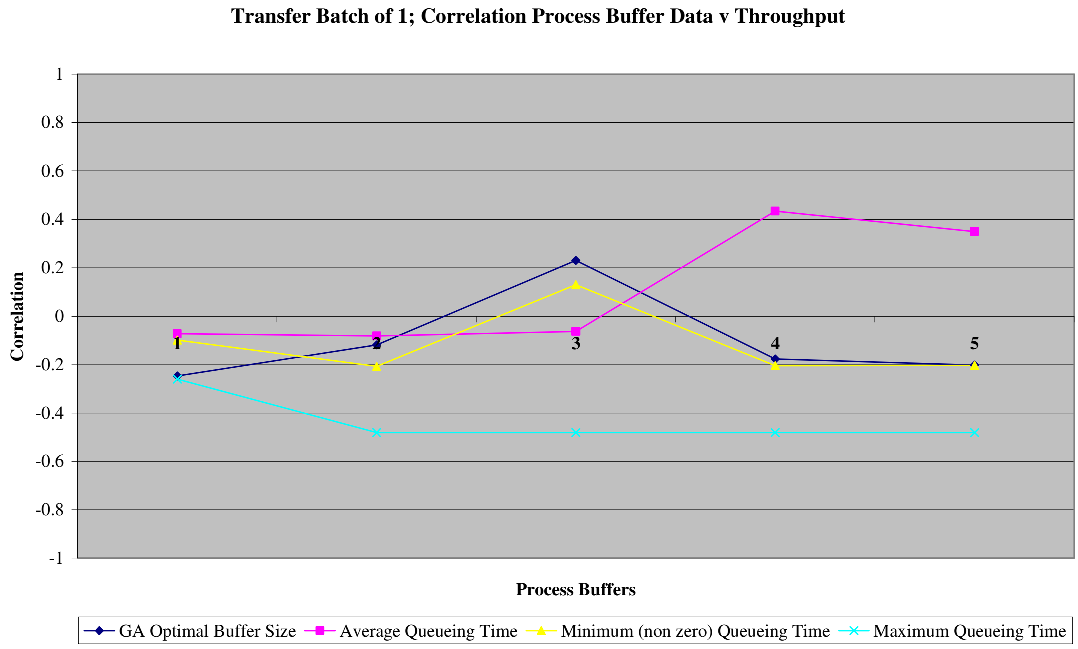

Figure 5.1: Correlations of Buffer Data with Transfer Batch of 1

Table 5.4: Experiment Results: % Working v Throughput Batch of 1

% Working			TRANSFER BATCH OF 1				
EXP No.	**Total Buffer**	**Through Put**	**A or B**	**B or C**	**A+B**	**B+C**	**ABorBC**
Exp 1.4	61	1262	75	65	53.5	66	45
Exp 2.3	43	1390	80	86	68	74	69
Exp 3.2	74	989	75	85	84	80	51
Exp 4.1	36	1380	65	82	68.1	71.98	60
Exp 5.4	82	1443	75	65	75	76	33
Exp 6.3	55	1818	65	79	57	80	69
Exp 7.2	94	1268	76.34	65.43	75.43	75.65	51
Exp 8.1	50	957	76.54	71.43	70.54	65	60
		Correlation =	-0.56797	0.057613	-0.54544	0.438321	0.24892

The negative correlation although not that strong is showing that although the %working is fairly high, the affect of the product mix and scheduling has led to non mating parts being produced and resulting in longer queuing times as shown previously.

Table 5.5: Experiment Results: % Blocking v Throughput

% Blocking			**TRANSFER BATCH OF 1**				
EXP No.	**Total Buffer**	**Through Put**	**A or B**	**B or C**	**A+B**	**B+C**	**ABorBC**
Exp 1.4	61	1262	3	1	0.5	1	0
Exp 2.3	43	1390	2	2	2	2	0
Exp 3.2	74	989	1	2	3	0.3	0
Exp 4.1	36	1380	12	1	1.9	1.02	0
Exp 5.4	82	1443	2	1	0.68	1	0
Exp 6.3	55	1818	1.77	2	1	4	0
Exp 7.2	94	1268	1.21	1.25	4.97	0.81	0
Exp 8.1	50	957	1.25	1.81	5.03	1.57	0
		Correlation =	0.160645	-0.04651	-0.62329	0.74604	#DIV/0!

Table 5.6: Experiment Results: % Waiting v Throughput

% Waiting			**TRANSFER BATCH OF 1**				
EXP No.	**Total Buffer**	**Through Put**	**AorB**	**BorC**	**A+B**	**B+C**	**ABorBC**
Exp 1.4	61	1262	22	34	46	33	55
Exp 2.3	43	1390	18	12	30	24	31
Exp 3.2	74	989	24	13	19	19.7	49
Exp 4.1	36	1380	23	17	30	27	40
Exp 5.4	82	1443	23	34	24.32	23	67
Exp 6.3	55	1818	33.23	19	42	16	31
Exp 7.2	94	1268	22.45	33.32	29.54	23.54	49
Exp 8.1	50	957	22.21	26.76	24.43	33.43	40
		Correlation =	0.584547	-0.05327	0.580156	-0.55394	-0.24892

Tables 5.5 and 5.6 show the blocking and waiting to be quite erratic and increases when the schedule changes, but although there is there is an increase there are more mating parts than the first set of schedules to produce a higher throughput result.

Table 5.7: Experiment Results: % Change-over v Throughput

% change-over			TRANSFER BATCH OF 1				
EXP No.	Total Buffer	Through Put	A or B	B or C	A+B	B+C	ABorBC
Exp 1.4	61	1262	25	22	N/A	N/A	N/A
Exp 2.3	43	1390	19.54	12.65	N/A	N/A	N/A
Exp 3.2	74	989	22	9	N/A	N/A	N/A
Exp 4.1	36	1380	12.56	17.23	N/A	N/A	N/A
Exp 5.4	82	1443	19.76	29.65	N/A	N/A	N/A
Exp 6.3	55	1818	24.54	17	N/A	N/A	N/A
Exp 7.2	94	1268	23.21	18.96	N/A	N/A	N/A
Exp 8.1	50	957	17.87	27.54	N/A	N/A	N/A
		Correlation =	0.183988	-0.0139	N/A	N/A	N/A

Table 5.7 shows that the best % change-over times for the first two operations have yielded the best throughput in the second set of schedules, i.e. 6.3, but a lower % change-over in the first set, i.e. 3.2 has made little difference to this experiments throughput due to the effects of the product mix and schedule.

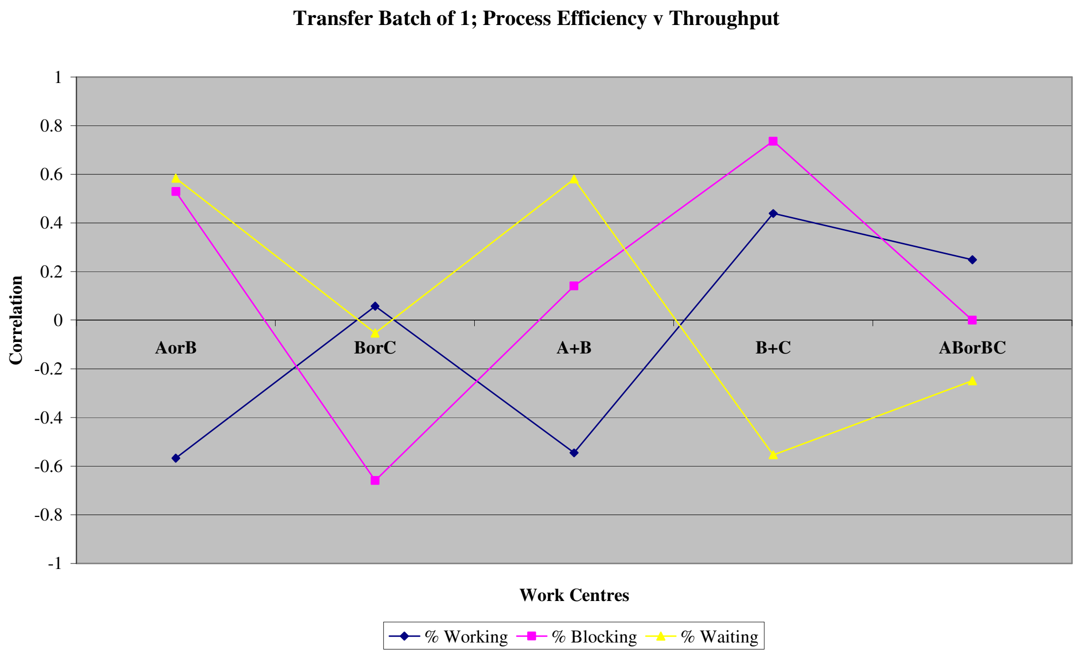

Figure 5.2: Chart of Work Centre Correlations Transfer Batch of 1

Figure 5.2 shows how the correlation between each work centre changes from positive to negative against the throughput.

5.2 Results: Transfer Batch of 10

Table 5.8: Experiment Results: Optimal Buffer Size v Throughput

GA Optimal buffer size			TRANSFER BATCH OF 10				
EXP No.	**Total Buffer**	**Through Put**	**Buffer 1**	**Buffer 2**	**Buffer 3**	**Buffer 4**	**Buffer 5**
Exp 1.3	145	1325	39	18	36	12	41
Exp 2.4	95	1459	20	10	17	28	20
Exp 3.1	138	1038	35	20	31	16	36
Exp 4.2	176	1490	44	28	38	22	44
Exp 5.3	314	1515	79	49	70	37	80
Exp 6.4	186	1963	47	21	47	13	58
Exp 7.1	174	1370	37	31	39	18	49
Exp 8.2	193	1004	45	33	41	30	44
		Correlation =	0.21852	-0.0429	0.28514	-0.1653	0.37255

Transfer batches of 10 results show an increase in WIP inventory from the first sets of experiments, Transfer Batch of 1. The highest throughput is experiment 6.4 which has the second highest WIP inventory. Experiment 2.4 shows the lowest buffer content at 95, indicating with a process batch of 15, this experiment can provide 30% less throughput with around half of the WIP inventory of the best scenario in this set of experiments.

Table 5.9: Experiment Results: Average Queuing Time v Throughput

Average queuing time			TRANSFER BATCH OF 10				
EXP No.	Total Buffer	Through Put	Buffer 1	Buffer 2	Buffer 3	Buffer 4	Buffer 5
Exp 1.3	145	1325	43.15	33.4	3.96	43.05	50.48
Exp 2.4	95	1459	2.34	7.41	39.6	38.6	44.14
Exp 3.1	138	1038	45.9	36.15	35.15	52.8	47.26
Exp 4.2	176	1490	41.45	31.7	49.35	50.35	55.89
Exp 5.3	314	1515	55.65	45.9	46.9	64.55	88.31
Exp 6.4	186	1963	44.2	34.45	52.1	44.1	51.53
Exp 7.1	174	1370	58.4	48.65	40.65	6.9	1.36
Exp 8.2	193	1004	46.95	37.2	3.45	3.45	4.09
		Correlation =	-0.09698	-0.09698	0.616242	0.360401	0.457732

The difference in product mix between experiment 4.2 and 6.4 has made a significant improvement in the throughput. There is no strong correlation between throughput and average queuing time, but apart from experiment 2.4 there is a reduction in average queuing time of 9.75 minutes.

Table 5.10: Experiment Results: Minimum Queuing Time v Throughput

Minimum (non-zero) Queuing Time			TRANSFER BATCH OF 10				
EXP No.	Total Buffer	Through Put	Buffer 1	Buffer 2	Buffer 3	Buffer 4	Buffer 5
Exp 1.3	145	1325	42	22	38	32.89	43
Exp 2.4	95	1459	22	13	21	43.73	23
Exp 3.1	138	1038	39	24	33	49.53	40
Exp 4.2	176	1490	47	30	42	47.43	47
Exp 5.3	314	1515	83	52	72	56.38	82
Exp 6.4	186	1963	50	25	51	51.29	61
Exp 7.1	174	1370	41	34	41	14.33	53
Exp 8.2	193	1004	48	35	44	3.45	46
		Correlation =	0.218373	-0.03687	0.321007	-0.13684	0.370752

The results for minimum queuing time show no real correlation with the throughput results.

Table 5.11: Experiment Results: Maximum Queuing Time v Throughput

Maximum queuing time			TRANSFER BATCH OF 10				
EXP No.	Total Buffer	Through Put	Buffer 1	Buffer 2	Buffer 3	Buffer 4	Buffer 5
Exp 1.3	145	1325	54.34	50.8	47.26	43.72	40.18
Exp 2.4	95	1459	49.89	46.35	42.81	39.27	35.73
Exp 3.1	138	1038	57.09	53.55	50.01	46.47	42.93
Exp 4.2	176	1490	52.64	49.1	45.56	42.02	38.48
Exp 5.3	314	1515	66.84	63.3	59.76	56.22	52.68
Exp 6.4	186	1963	55.39	51.85	48.31	44.77	41.23
Exp 7.1	174	1370	69.59	66.05	62.51	58.97	55.43
Exp 8.2	193	1004	58.14	54.6	51.06	47.52	43.98
		Correlation =	-0.084	-0.084	-0.084	-0.084	-0.084

On each experiment for the maximum queuing time results, the queue time reduces by 3.54 minutes between each buffer, yet there is no real correlation, the results are identical.

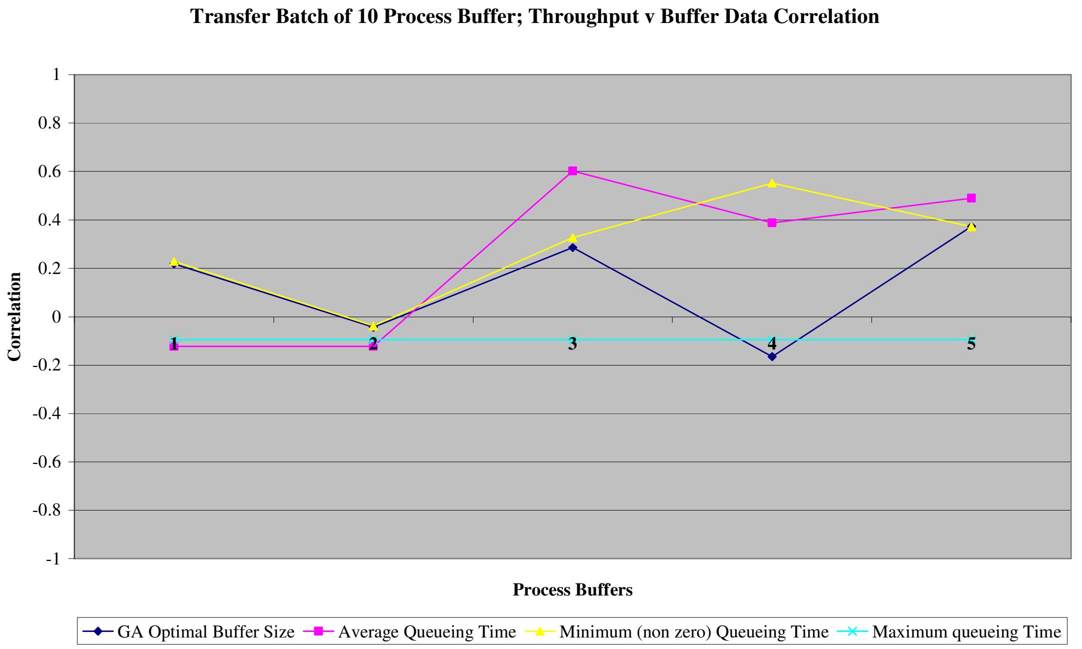

Figure 5.3: Correlations of Buffer Data with Transfer Batch of 10

The chart shows buffer 3 average queue time to have the strongest correlation with throughput for these sets of experiments and maximum queue time has no correlation.

Table 5.12: Experiment Results: % Working v Throughput

% Working			TRANSFER BATCH OF 10				
EXP No.	Total Buffer	Through Put	A or B	B or C	A+B	B+C	ABorBC
Exp 1.3	145	1325	36.05	73.94	33.19	45.03	89.00
Exp 2.4	95	1459	54.41	74.66	42.60	53.34	89.80
Exp 3.1	138	1038	58.31	76.91	40.51	48.16	85.41
Exp 4.2	176	1490	53.41	76.06	44.68	53.43	89.48
Exp 5.3	314	1515	37.14	57.97	8.99	43.07	81.37
Exp 6.4	186	1963	46.48	70.95	26.70	36.52	82.80
Exp 7.1	174	1370	30.25	67.38	15.58	47.27	86.02
Exp 8.2	193	1004	60.0	80.0	45.0	55.0	89.91
		Correlation =	-0.34782	-0.45256	-0.39633	-0.66858	-0.47066

There is some correlation with throughput and % working at process B + C which is an assembly process.

Table 5.13: Experiment Results: % Blocking v Throughput

% Blocking			TRANSFER BATCH OF 10				
EXP No.	Total Buffer	Through Put	A or B	B or C	A+B	B+C	ABorBC
Exp 1.3	145	1325	23.02	4.99	1.45	0.07	0.09
Exp 2.4	95	1459	0.09	0.09	0.09	0.09	0.09
Exp 3.1	138	1038	0.09	0.09	0.09	0.09	0.09
Exp 4.2	176	1490	0.09	0.09	0.09	0.00	0.09
Exp 5.3	314	1515	0.79	0.09	0.09	0.99	0.09
Exp 6.4	186	1963	0.30	0.09	0.09	0.09	0.09
Exp 7.1	174	1370	0.30	0.89	0.65	0.09	0.09
Exp 8.2	193	1004	0.20	0.12	0.35	0.20	0.09
		Correlation =	-0.0861	-0.10446	-0.20745	0.083204	0.073939

Table 5.13 shows that there is no correlation between % blocking and throughput.

Table 5.14: Experiment Results: % Waiting v Throughput

% Waiting			TRANSFER BATCH OF 10				
EXP No.	Total Buffer	Through Put	A or B	B or C	A+B	B+C	ABorBC
Exp 1.3	145	1325	40.93	21.07	65.36	54.90	10.91
Exp 2.4	95	1459	45.50	25.25	57.31	46.58	10.11
Exp 3.1	138	1038	41.60	23.00	59.40	51.75	14.50
Exp 4.2	176	1490	46.50	23.85	55.23	46.58	10.43
Exp 5.3	314	1515	62.08	41.94	90.92	55.94	18.55
Exp 6.4	186	1963	53.23	28.96	73.21	63.39	17.11
Exp 7.1	174	1370	69.45	31.73	83.77	52.64	13.89
Exp 8.2	193	1004	40.00	20.00	55.00	45.00	10.00
		Correlation =	0.425592	0.45822	0.404742	0.673107	0.470664

There is some positive correlation between throughput and % waiting time at process B+C and all other processes are around the same.

Table 5.15: Experiment Results: % Change-over v Throughput

% change-over			TRANSFER BATCH OF 10				
EXP No.	Total Buffer	Through Put	A or B	B or C	A+B	B+C	ABorBC
Exp 1.3	145	1325	28.75	26.00	N/A	N/A	N/A
Exp 2.4	95	1459	23.45	24.12	N/A	N/A	N/A
Exp 3.1	138	1038	34.75	22.45	N/A	N/A	N/A
Exp 4.2	176	1490	35.78	23.10	N/A	N/A	N/A
Exp 5.3	314	1515	34.35	41.45	N/A	N/A	N/A
Exp 6.4	186	1963	46.54	28.12	N/A	N/A	N/A
Exp 7.1	174	1370	56.87	32.23	N/A	N/A	N/A
Exp 8.2	193	1004	22.54	34.32	N/A	N/A	N/A
		Correlation =	0.436261	0.036539	N/A	N/A	N/A

Table 5.15 shows that % change-over has had no correlation with throughput on these sets of experiments, and figure 5.4 shows that the assembly operation B+C has had the most influence on the throughput results.

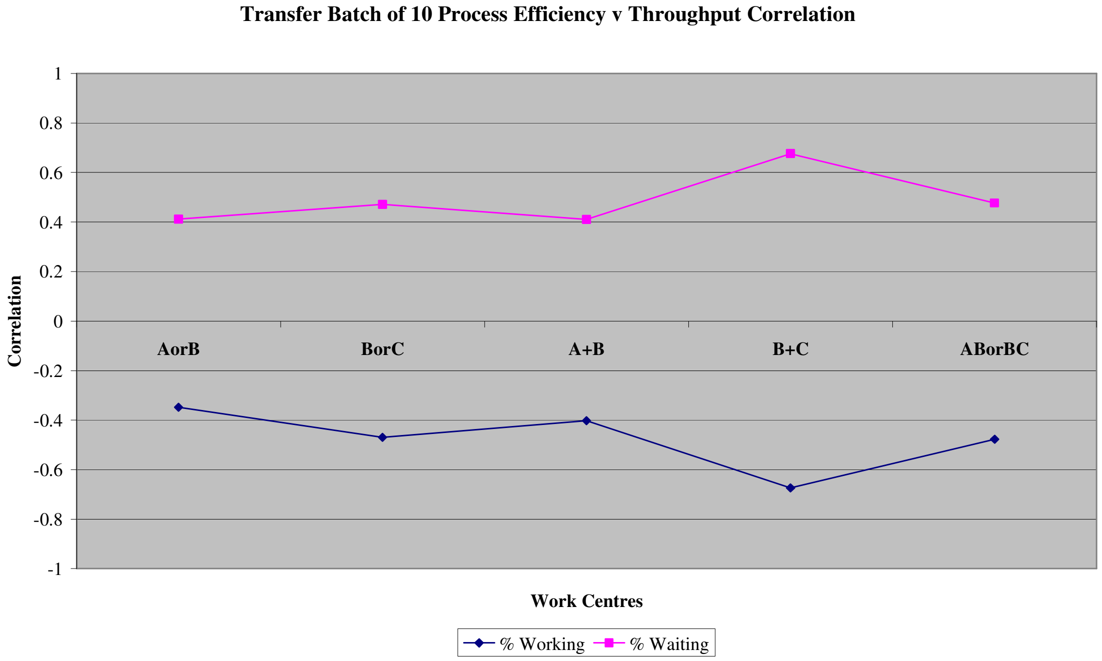

Figure 5.4: Chart of Work Centre Correlations Transfer Batch of 10

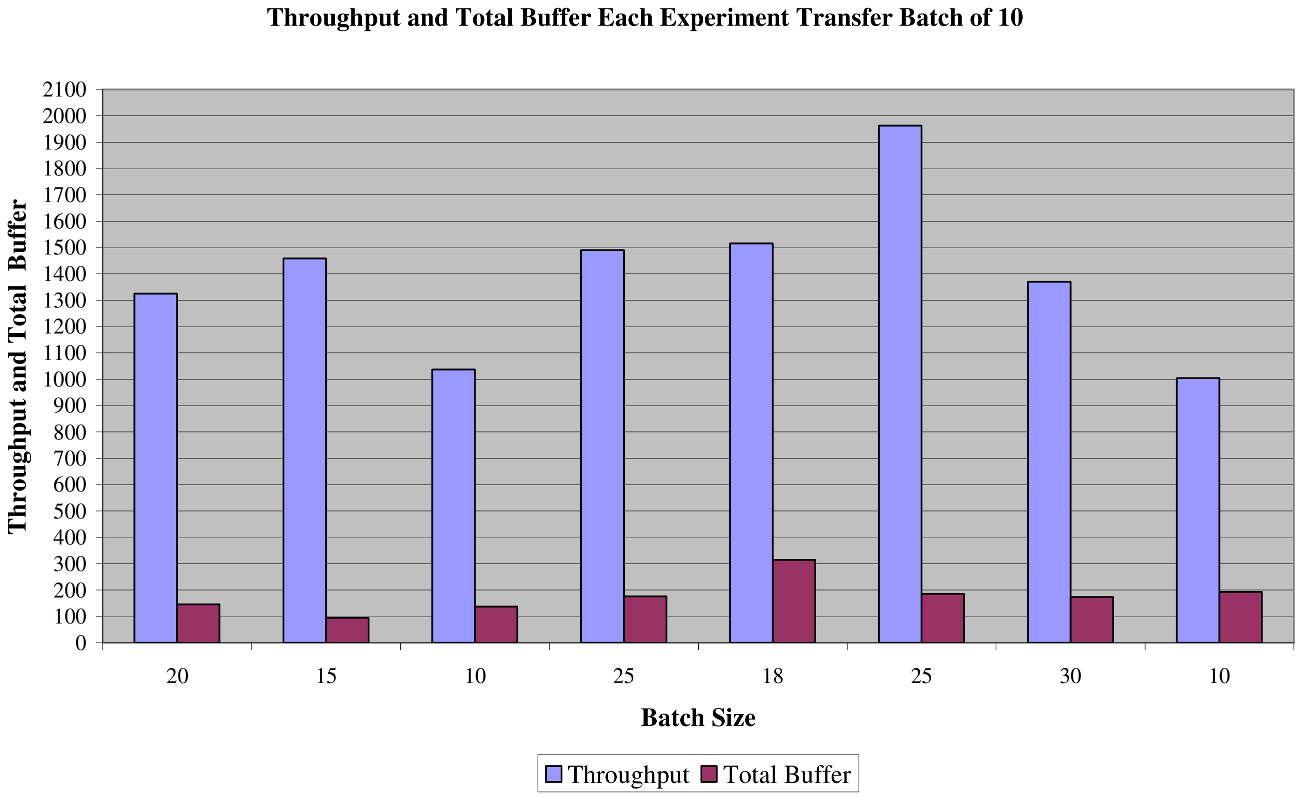

Figure 5.5: Throughput v Total Buffer Quantities

Figure 5.5 is devised to show the WIP in the system against the throughput results when the transfer batch is 10 and the process batches for each experiment are shown on the X axis. This shows that different product mixes can affect the throughput when the transfer batch and process batches are the same.

5.3 Results: Process Batch = Transfer Batch

Table 5.16: Experiment Results: Optimal Buffer Size v Throughput

GA Optimal buffer size			TBS = PBS				
EXP No.	**Total Buffer**	**Through Put**	**Buffer 1**	**Buffer 2**	**Buffer 3**	**Buffer 4**	**Buffer 5**
Exp 1.1	371	1409	93	96	82	30	70
Exp 2.2	380	1642	76	94	92	89	29
Exp 3.3	431	1244	80	95	84	76	96
Exp 4.4	248	1723	25	56	59	65	43
Exp 5.1	290	1545	41	45	89	98	17
Exp 6.2	254	2209	34	26	78	95	21
Exp 7.3	246	1340	94	38	41	17	56
Exp 8.4	248	1059	30	16	94	100	8
		Correlation =	-0.3455	-0.1226	-0.1038	0.22555	-0.2894

This array of experiments did not have a set transfer batch size, .i.e. the process batch size was the transfer batch size (TBS = PBS). Table 5.20 shows that experiment 6.2 has the best Throughput of 2209 with a process batch = transfer batch of 40.

Experiment 8.4 has the worst throughput of 1059 with a process = transfer batch of 52, although the total buffer content of the system was virtually at the same level for both experiments, the throughput of experiment 6.2 is nearly double the throughput of experiment 8.4, indicating that the change in product mix has affected the throughput. There was no correlation between throughput and the optimal buffer sizes.

Table 5.17: Experiment Results: % Working v Throughput

% Working			**TBS = PBS**				
EXP No.	**Total Buffer**	**Through Put**	**A or B**	**B or C**	**A+B**	**B+C**	**ABorBC**
Exp 1.1	371						
Exp 2.2	380	**1642**	12	33	73.5	69	97.91
Exp 3.3	431						
Exp 4.4	248	**1723**	43	23.4	54.1	49.2	71.99
Exp 5.1	290						
Exp 6.2	254	**2209**	92.5	73.2	44	84.2	99.99
Exp 7.3	246						
Exp 8.4	248	**1059**	78.2	82	39	25	99.92
		Correlation =	0.130343	-0.1911645	0.1469713	0.9233709	-0.0898106

There is a strong positive correlation at process B+C between % working and throughput.

Table 5.18: Experiment Results: % Blocking v Throughput

% Blocking			**TBS = PBS**				
EXP No.	**Total Buffer**	**Through Put**	**A or B**	**B or C**	**A+B**	**B+C**	**ABorBC**
Exp 1.1	371						
Exp 2.2	380	**1642**	3	2	1.5	1	0.09
Exp 3.3	431						
Exp 4.4	248	**1723**	2	1.6	0.9	0.8	0.01
Exp 5.1	290						
Exp 6.2	254	**2209**	2.5	1.8	1	0.8	0.01
Exp 7.3	246						
Exp 8.4	248	**1059**	1.8	3	6	0	0
		Correlation =	0.4982543	-0.8360088	-0.8697418	0.7590896	0.0791167

There seems to be a negative correlation between % blocking and throughput for processes B or C and A+B and a positive correlation at process B+C.

Table 5.19: Experiment Results: % Waiting v Throughput

% Waiting			TBS = PBS				
EXP No.	**Total Buffer**	**Through Put**	**A or B**	**B or C**	**A+B**	**B+C**	**ABorBC**
Exp 1.1	371						
Exp 2.2	380	**1642**	85	65	25	30	2
Exp 3.3	431						
Exp 4.4	248	**1723**	55	75	45	50	28
Exp 5.1	290						
Exp 6.2	254	**2209**	5	25	55	15	0
Exp 7.3	246						
Exp 8.4	248	**1059**	20	15	55	75	0.08
		Correlation =	-0.1388213	0.2060515	-0.0079987	-0.923376	0.0895098

There is a strong negative correlation at process B+C between % waiting and throughput, but no correlation anywhere else. This shows the expected outcome that increased waiting time in the queues decreases the throughput of material through the system, and with a DBR system all efforts would be concentrated on the constraint causing the excessive waiting time.

Table 5.20: Experiment Results: % Change-over v Throughput

% change-over			TBS = PBS				
EXP No.	**Total Buffer**	**Through Put**	**A or B**	**B or C**	**A+B**	**B+C**	**ABorBC**
Exp 1.1	371				N/A	N/A	N/A
Exp 2.2	380	**1642**	14.32	27.877	N/A	N/A	N/A
Exp 3.3	431				N/A	N/A	N/A
Exp 4.4	248	**1723**	39.75	24	N/A	N/A	N/A
Exp 5.1	290				N/A	N/A	N/A
Exp 6.2	254	**2209**	1.6	74.76	N/A	N/A	N/A
Exp 7.3	246				N/A	N/A	N/A
Exp 8.4	248	**1059**	22.76	35.78	N/A	N/A	N/A
		Correlation =	-0.4603133	0.6323765	N/A	N/A	N/A

The best case scenario for process batch size = transfer batch size indicates that work station Assembly BC has a high percentage of utilization with a high buffer content before it; highlighting that it is the bottleneck operation.

The system has high inventory levels and quite high throughput; the high inventory that could be caused by the large batch sizes and transfer batch size. This would cause an initially large overall lead time at start-up due to longer lead-times between processes whilst the large transfer batches are processed through the system. The larger batch sizes also mean fewer product change-over/ set-up times; so more complex product mixes may not show good throughput results.

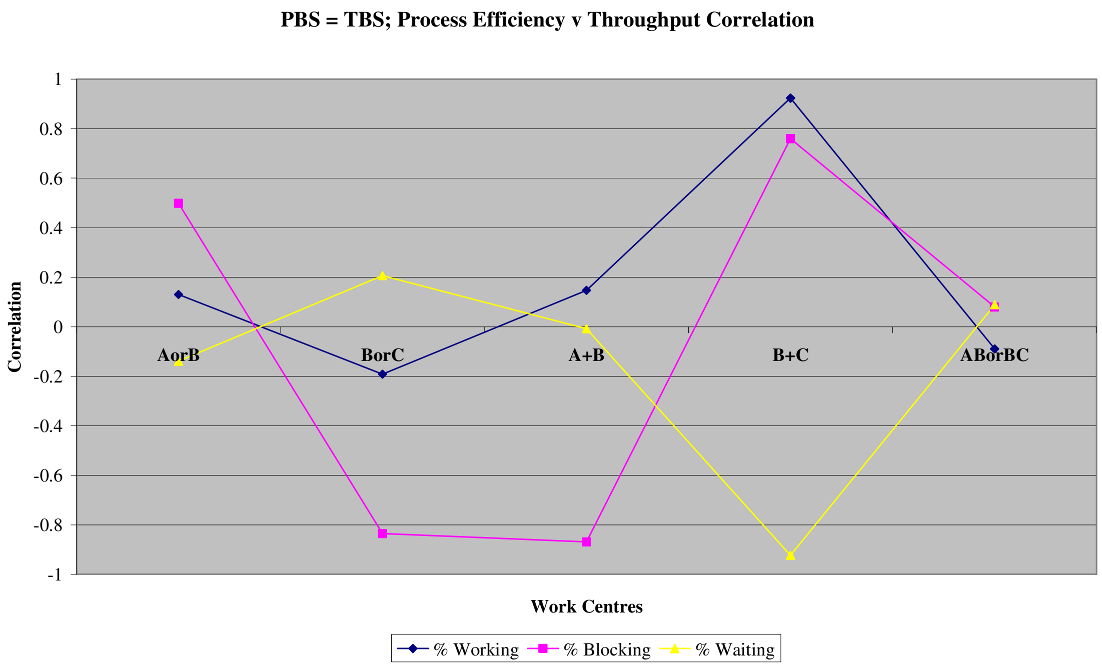

Figure 5.6: Chart of Work Centre Correlations PBS = TBS.

Figure 5.6 shows the work centres that are affected by the blocking and waiting and where efforts could be focused for improving flow.

5.4 Trends Evident In the Results

The trends of all the throughputs show that each product mix has a similar throughput for each transfer batch size. This indicates that the product mix has the major influence on throughput with this model.

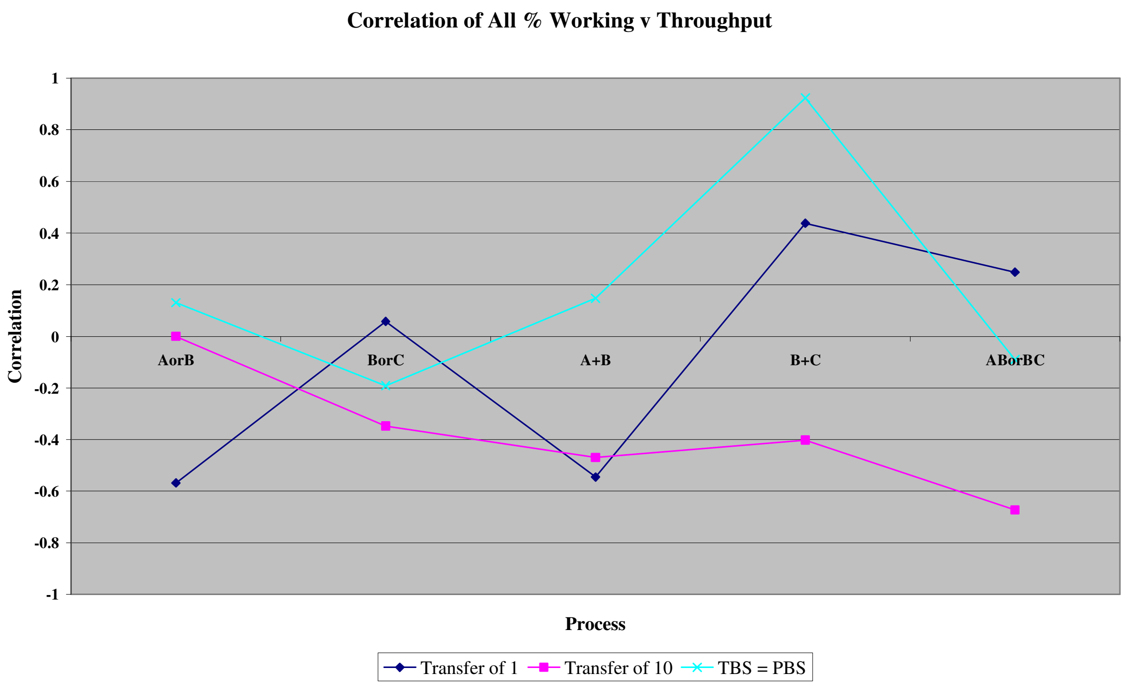

Figure 5.7: Chart Correlation of all % Working v Throughput

TBS = PBS shows a definite positive correlation for assembly process B+C compared to the transfer batch experiments, this may be due to the higher inventory in the system which would make this relationship more evident.

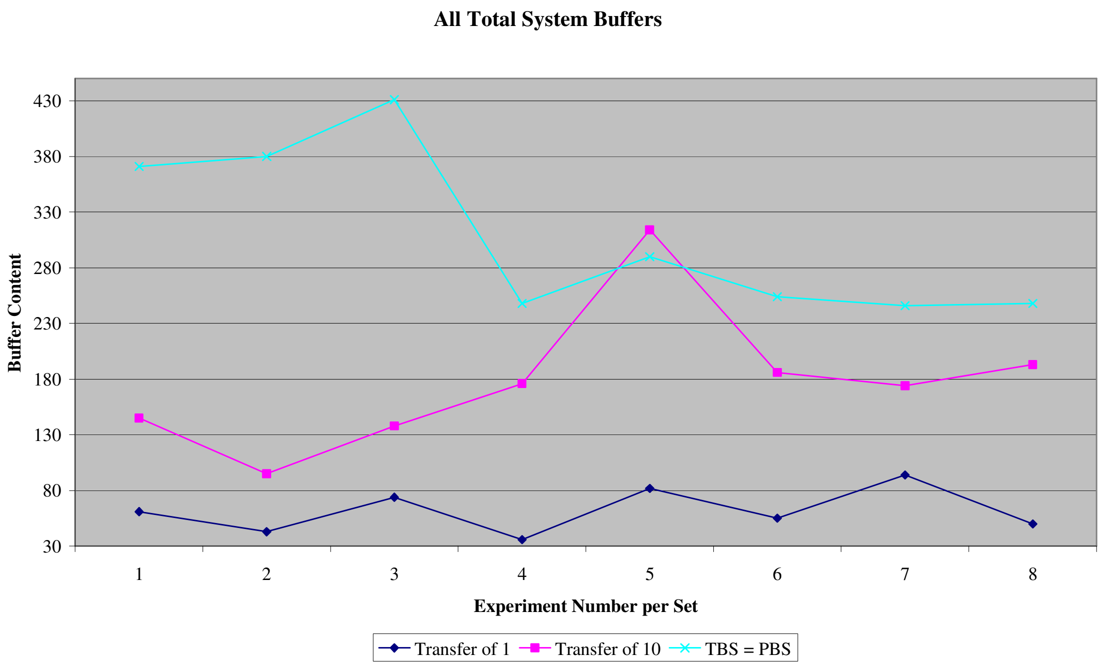

Figure 5.8: Chart of Total WIP per Set of Experiments

The trend for the WIP inventory in the system is also affected by the product mix but shows that the smaller transfer batch sizes influence WIP which is expected.

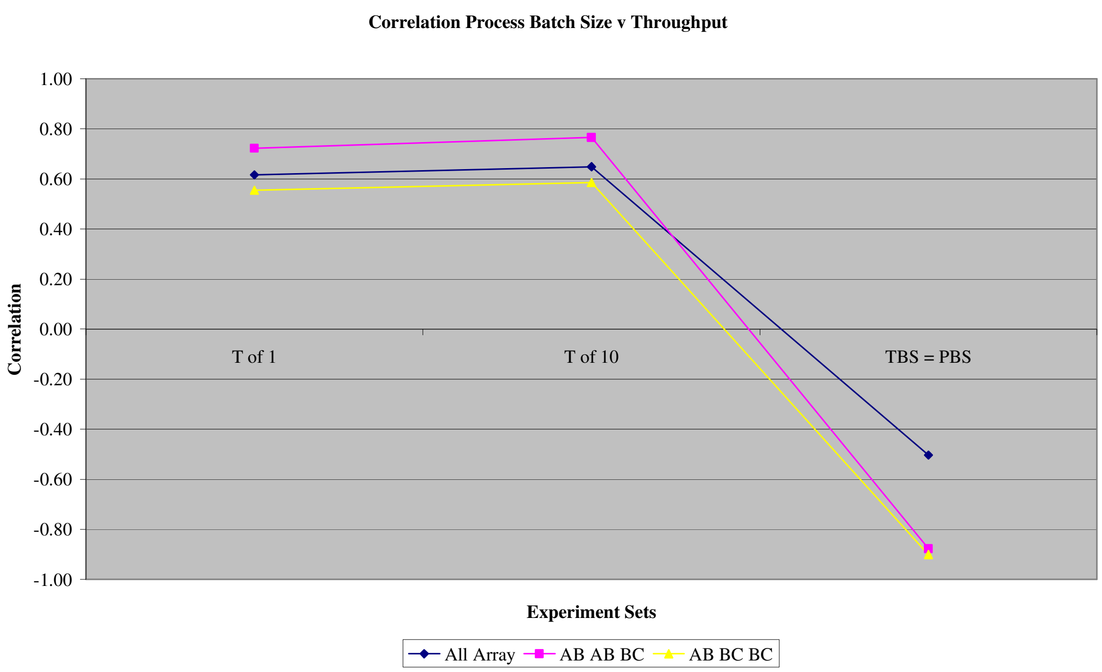

Figure 5.9: Chart of Correlation v Process Batch Sizes

The correlation of throughput against process batch size shows that there was a positive correlation with transfer batch manufacturing and a negative correlation where the transfer batch size was equal to the process batch size.

Below figures 11 to 14, show how the buffer content for each experiment changes and the how the model has tried to change the buffer size to maintain throughput.

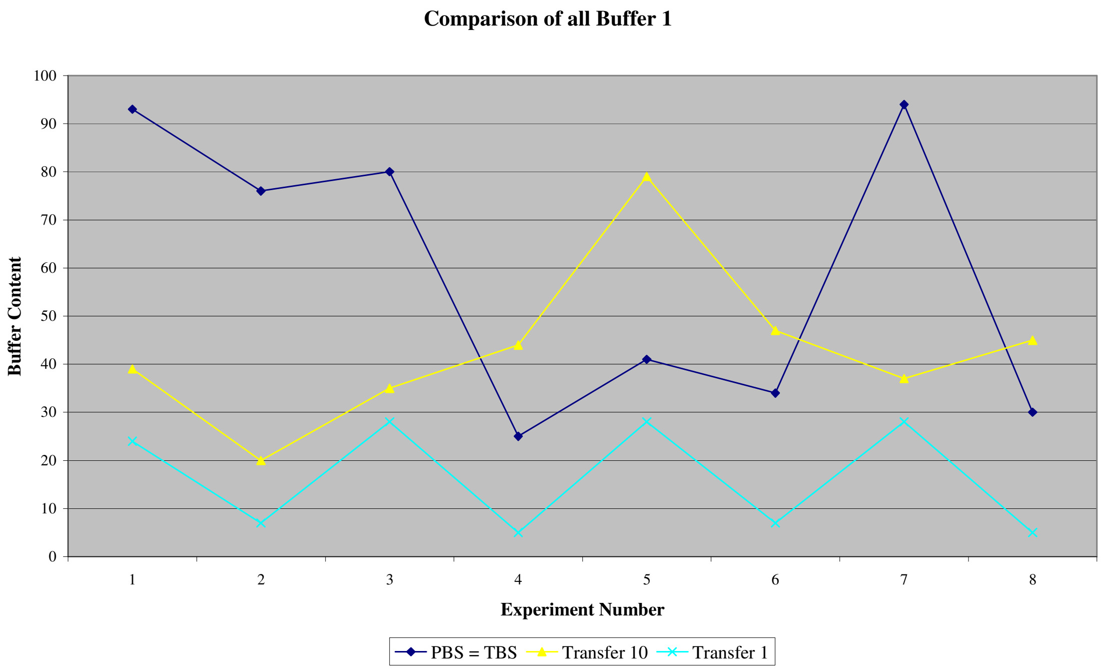

Figure 5.10: Chart; all Buffer 1 Contents

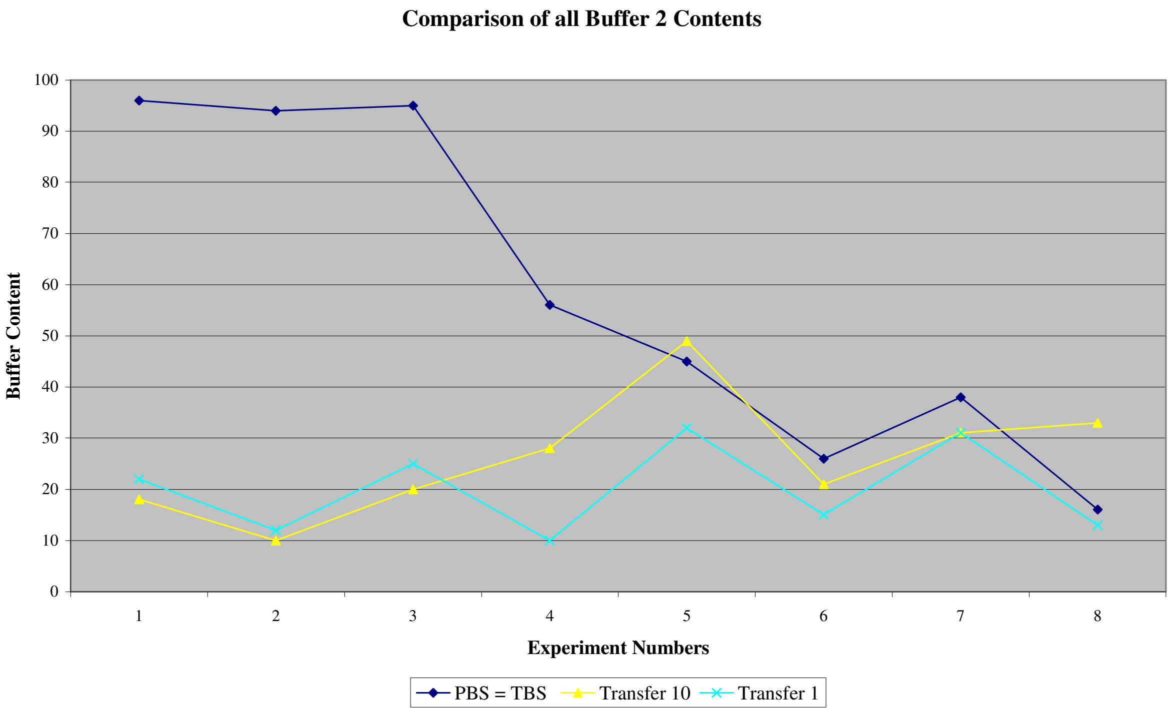

Figure 5.11: Chart; all Buffer 2 Contents

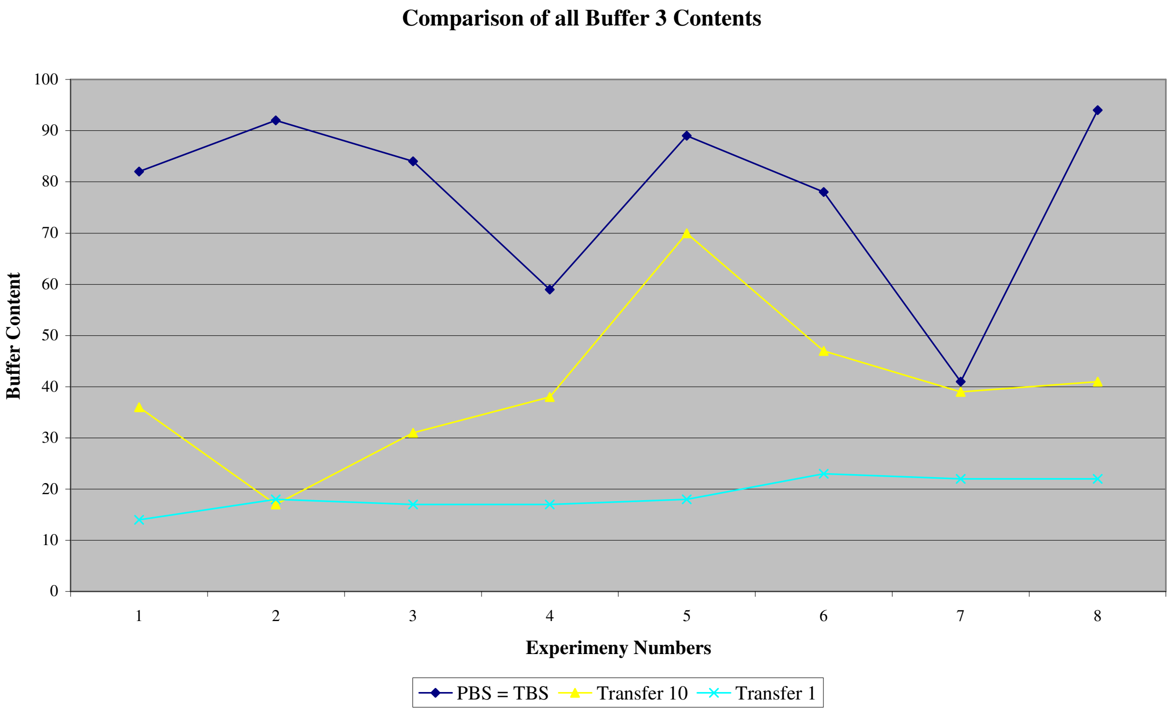

Figure 5.12: Chart; all Buffer 3 Contents

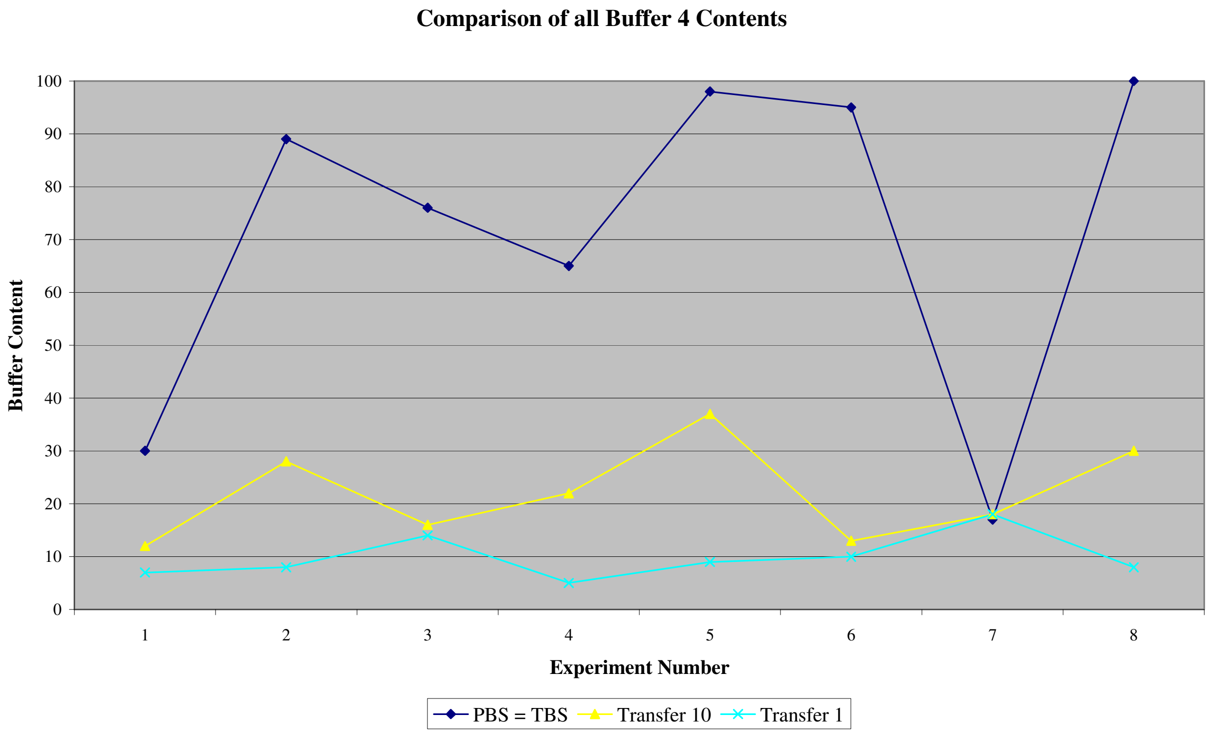

Figure 5.13: Chart; all Buffer 4 Contents

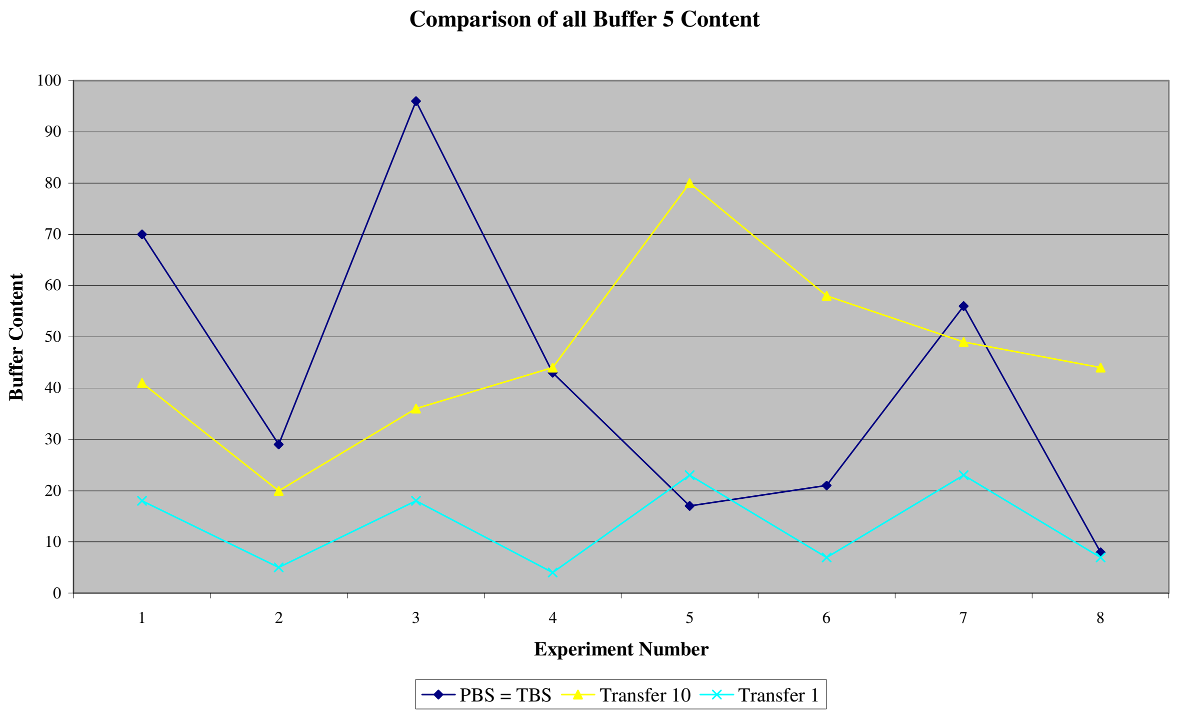

Figure 5.14: Chart; all Buffer 5 Contents

Comparison of each of the buffer content also shows how volatile the system is to the changes in product mix and how it is an advantage to carry-out simulation before implementing certain schedules as labour can be moved between processes to further improve system output prior to production.

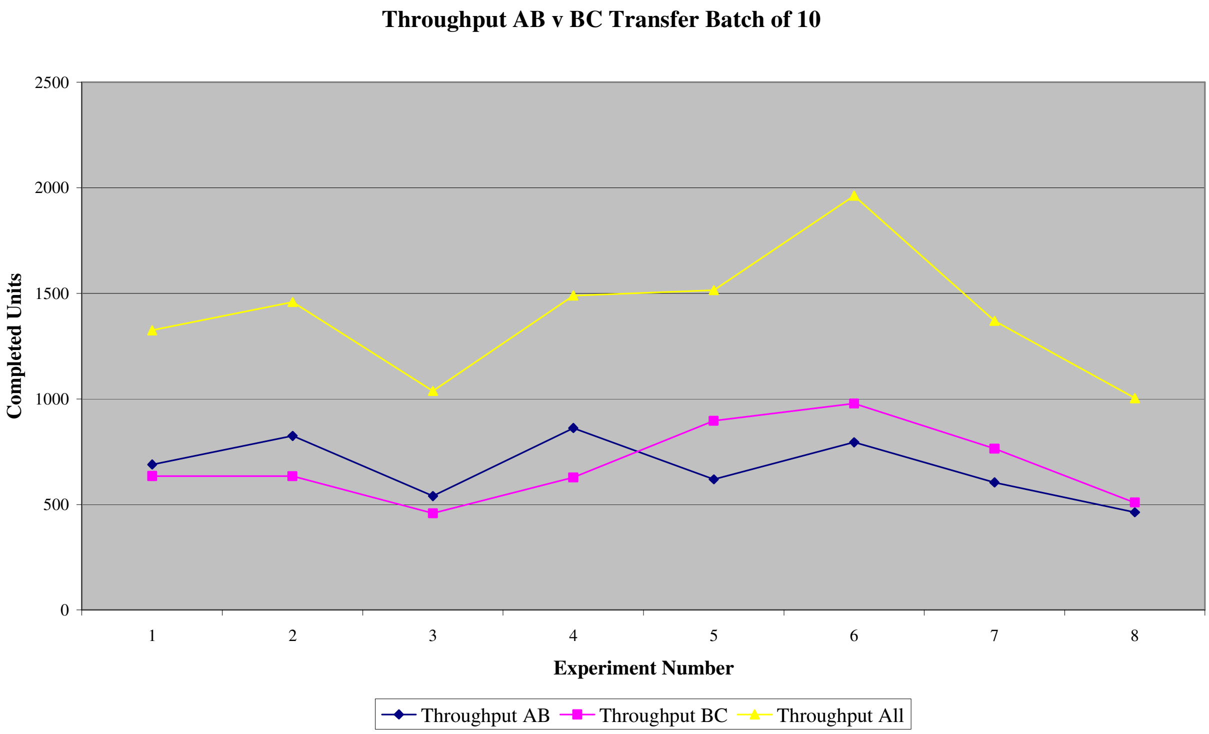

Figure 5.15: Chart; Completed Units Transfer of 10

Figure 5.15, shows how the change in schedule affects the throughput of these two products, although they follow the same trend due to the product mix the best throughput swaps from AB to BC.

Chapter 6 - Discussion

6.1 Removing DBR Failure Modes

6.1.1 OPT and GA

OPT attempts to identify the product mix that maximises the profit to be derived from use of an organisation's bottleneck resources. Unfortunately the increasing demand from customers for high product variety and customisation makes it extremely difficult to control product mixes. The genetic algorithm method developed provides an alternative method to OPT by maximising the throughput level for an individual product mix whatever that product mix happens to be.

The flexibility of the GA solution method makes it possible to convert the 'throughput-based' fitness function used within the current research into a 'cost-based' and/or 'profit-based' fitness function and so achieve the original aims of OPT. An example of a typical costing is shown below. This is essential, when appropriate to ensure that there is sufficient operating capital to finance the amount of work-in-process within the manufacturing system.

Table 6.1: Buffer Content by Part Type Transfer Batch = 10

Exp	buffer 1	buffer 2	Buffer 3		Buffer 4		Buffer 5		TP AB	TP BC
1.3	39A	18B	28A	53B	23A	38C	12AB	27BC	690	635
2.4	20A	10C	23A	26B	14A	19C	13AB	27BC	825	634
3.1	35B	20B	21A	39B	33A	26C	33AB	27BC	540	458
4.2	44B	28C	16A	21B	16A	19C	17AB	12BC	862	628
5.3	79A	49B	14A	18B	23A	24C	11AB	16BC	619	896
6.4	47A	21C	13A	16B	18A	17C	14AB	9BC	795	978
7.1	37B	31B	12A	19B	18A	27C	13AB	17BC	605	765
8.2	45B	33C	14A	23B	6A	11C	5AB	13BC	463	509

An example of throughput of the individual component parts shown in table 6.1 could also determine which product mix is the most profitable rather than basing decisions purely on throughput.

The profit of each throughput table 6.2 for Transfer batch of 10 derived by a spreadsheet is based on;

A = £1, B = £1, C = £2; the selling price of AB = £10 and the selling price of BC = £10 or £20.

Table 6.2: Throughput Values Transfer of 10

Exp. No	Cost AB	Cost BC	Value AB	Value BC	Revenue AB	Revenue BC £10	Revenue BC £20	Total Profit 1	Total Profit 2
1.3	£1,380	£1,905	£6,900	£12,700	£5,520	£4,445	£10,795	£9,965	£16,315
2.4	£1,650	£1,902	£8,250	£12,680	£6,600	£4,438	£10,778	£11,038	£17,378
3.1	£1,080	£1,374	£5,400	£9,160	£4,320	£3,206	£7,786	£7,526	£12,106
4.2	£1,724	£1,884	£8,620	£12,560	£6,896	£4,396	£10,676	£11,292	£17,572
5.3	£1,238	£2,688	£6,190	£17,920	£4,952	£6,272	£15,232	£11,224	£20,184
6.4	£1,590	£2,934	£7,950	£19,560	£6,360	£6,846	£16,626	£13,206	£22,986
7.1	£1,210	£2,295	£6,050	£15,300	£4,840	£5,355	£13,005	£10,195	£17,845
8.2	£926	£1,527	£4,630	£10,180	£3,704	£3,563	£8,653	£7,267	£12,357

The basic techniques that can be applied, in a practical sense, to synchronise work flows within high variety flow processing systems include finite capacity scheduling, order based scheduling/just-in-time and constraint based scheduling.

Finite capacity scheduling takes available capacity into consideration when deciding the lead-time for customer orders, i.e. schedules are based on the capacity available. This improves on the infinite capacity scheduling approach adopted using MRP II which develops schedules using customers' order due dates without considering capacity limits. Feasible schedules, that do not break capacity constraints, need then to be developed. There are a variety of methods for producing finite capacity schedules, (Goldratt 1988), none of which guarantee optimum use of capacity. **Order Based Scheduling** of customer orders is based on their order priority, i.e. the sequence at individual resources is determined by the overall priority of the order for which the parts are assigned. It has the ability to improve on the customer service levels achieved through finite and infinite capacity schedulers but can be highly wasteful in terms of capacity usage. **Just-in-time** (JIT) control processes are similar to order based scheduling but 'pull' materials through the flow line based on the priority required to meet customer delivery requests.

Constraint based scheduling, based in the Theory of Constraints (TOC) locates the bottleneck process in the flow line and ensures that it is fully loaded, hence helping to maximise throughput levels. It is assumed that non-bottlenecks have the capacity to cope with the bottleneck schedule if synchronised to the demands of the bottleneck. This system is highly sensitive to product mix and demand changes such as rescheduled orders, (Satya et. al 2004).

Chakravorty and Atwater, (1996) identified the advantages of TOC over JIT and balanced flow lines under conditions of high product variety and low demand volumes with the following results reported, i.e.:

a) TOC lines significantly out produce both JIT and balanced lines at relatively low levels of total system inventory,
b) TOC lines achieve their maximum output level with much lower inventories in the system than JIT lines,
c) TOC lines perform best when station variation is relatively high, and
d) TOC lines perform best when station down-time is relatively high.

Drum-Buffer-Rope (DBR) planning processes are used to control material flow through constraint based systems. As defined in Chapter 3, Goldratt, (1988) identified the basic sequence of tasks required to implement a DBR planning methodology, i.e.:

i. Identify the bottlenecks and capacity constrained resource (CCR).
ii. Schedule the CCR such that maximum use is made of its available capacity.
iii. Synchronise production at all other resources to the production schedule at the CCR.
iv. Identify the pre-process locations where buffer inventory needs to be held.
v. Quantify the amount of buffer inventory that should be held at each of these locations.

In terms of DBR planning the factors that need to be determined include the sequence with which jobs need to be scheduled at the bottleneck process such that its capacity is fully employed, the sequences with which jobs need to be scheduled at non-bottleneck processes such that only capacity used to feed the bottleneck process is used, process and transfer batch sizes at bottleneck and non-bottlenecks and buffer locations and sizes throughout the system. Because constraint based planning is sensitive to change the schedules, batch sizes and buffer locations often may need to be re-determined each time product mix and demand levels change. In practice, this is not always possible leading to wasted bottleneck capacity due for example to materials arriving at bottlenecks late and reduction of buffer protection in the event of unexpected stoppages, (Umble and Srinkanth, 1996) however the objectives for the model detailed on page 77 have been met to provide the required results for this research.

Supply Chain Management

Supply chain issues have a major influence on all manufacturing systems and problems such as shortages caused by lateness, poor quality or lack of availability is just one that seriously affects production flow.

DBR deals with the effects of supply chain variability with regard to flow, i.e. the variability that affects the control of raw material from the point of origin to the point of consumption, in the same manor that it deals with process variability by extending the methodology at either end of the internal manufacturing system, i.e. input and output which is addressed by Schragenheim and Dettmer (2000) in much of their research using the Simplified DBR method. By implementing random arrival rates and a variable demand with buffers before the first processes (supply chain buffers) and the use of a shipping buffer, future research with this model can simulate this variability, however, supply chain issues were not the focus of this research.

6.1.2 Failure Mechanisms

Although DBR has the potential of providing an effective method of planning and scheduling low volume/high variety flow based manufacturing systems it has recognised limitations if the basic rules underlying the approach cannot be applied successfully. This can lead to the inability of work systems to operate at maximum performance through ineffective DBR-based planning. The more complex the work system the more likely that one or more of the failure mechanisms set out below will occur resulting in reductions in resource usage efficiency and customer service levels.

This thesis has set out to identify methods by which the current issues preventing the wider use of DBR systems can be resolved. In this respect the following issues have been addressed, i.e.:

1. **Failure to locate the bottleneck of the system will result in lost throughput, or increased WIP and cycle time depending on the ‘false’ bottlenecks' location relative to the real bottleneck. Failure through large amounts of variance, such as rework and machine breakdowns, causing bottlenecks to shift quickly.**

The ability of the genetic algorithm-based solution method developed during this project to resolve the above DBR failure mechanism can be demonstrated through comparing the results from Experiments 4.4 and 8.4 where Processing Batch Size (PBS) equals the Transfer Batch Size (TBS). Here, Experiments 4.4 and 8.4 share the same operating conditions, i.e. PBS=TBS, process times and set-up times and in respect of the job sequences through machines.

For output product mix ratio AB:AB:BC the operating conditions for Experiment 4.4 were such that throughput rate was maximised, i.e. 1723 units (Table 6.1). However, when product mix ratio is changed to AB:BC:BC these same operating conditions, Experiment 8.4, result in the least throughput rate being achieved, i.e. 1059 units. Using % Working as an indication of the bottleneck process Table 6.2 indicates that the bottleneck in Experiment 4.4 is 'Assembly A+B' with %Working of 54.1% whilst Machine 1, with %Working of 92.5 represents the bottleneck in Experiment 6.2.

From Table 6.1 it can be seen that Experiment 6.2 provides conditions for generating the highest level of throughput, i.e. 2209 units. When comparing the buffer levels, processing batch sizes and job sequences between Experiments 4.4, 8.4 and 6.2 it can be seen that when a product mix change occurs then to re-establish optimum conditions for achieving maximum throughput levels requires:

- Job sequence changes at Machine 1and Machine 2, i.e. from A-A-B to B-C-C
- Significant reduction in B2 buffer size, i.e. 56 units to 26 units
- Significant reduction in B5 buffer size, i.e. 43 units to 21 units
- Significant increase in B4 buffer size, i.e. 65 units to 95 units
- Increase in B1 buffer size, i.e. 25 units to 34 units

- Increase in B3 buffer size, i.e. 59 units to 78 units
- Increase in the processing batch size, i.e. 30 units to 40 units.

Table 6.3: Results PBS = TBS

PBS = TBS								
Product Mix	**Exp No**	**B1**	**B2**	**B3**	**B4**	**B5**	**T/Put**	**Process batch size**
AB AB BC	**1.1**	93	96	82	30	70	1409	35
	2.2	76	94	92	89	29	1642	22
	3.3	80	95	84	76	96	1244	55
	4.4	25	56	59	65	43	1723	30
AB BC BC	**5.1**	41	45	89	98	17	1545	48
	6.2	34	26	78	95	21	2209	40
	7.3	94	38	41	17	56	1340	45
	8.4	30	16	94	100	8	1059	52

Table 6.4: Experiment Comparisons PBS = TBS

Experiment 2.2: PBS = TBS Process Batch Size = 22					
working	blocking & waiting	C/O	Buffer	Process	Throughput
12	88	14.32	76	Machine 1	**1642**
33	67	27.9	94	Machine 2	
73.5	26.5	0	92	Assembly A+B	
69	31	0	89	Assembly A+B	
0	0	0	29	Assembly B+C	

Experiment 4.4: PBS = TBS Process Batch Size = 30					
working	blocking & waiting	C/O	Buffer	Process	Throughput
43	57	22.6	25	Machine 1	**1723**
23.0	77	34.3	56	Machine 2	
54.0	46	0	59	Assembly A+B	
49.0	51	0	65	Assembly A+B	
0	0	0	43	Assembly B+C	

Experiment 6.2: PBS = TBS (Best Case)					
Process Batch Size = 40					
working	blocking & waiting	C/O	Buffer	Process	Throughput
92.5	7.5	4.6	34	Machine 1	**2209**
73.0	27	25.7	26	Machine 2	
44	56	0	78	Assembly A+B	
84.0	16	0	95	Assembly B+C	
0	0	0	21	Assembly B+C	
Experiment 8.4: PBS = TBS (Worst Case)					
Process Batch Size = 52					
working	blocking & waiting	C/O	Buffer	Process	Throughput
78.0	22	14.8	30	Machine 1	**1059**
82.0	18	17.7	16	Machine 2	
39.0	61	0	94	Assembly A+B	
25.0	75	0	100	Assembly B+C	
0	0	0	8	Assembly B+C	

2. **Failure to provide flexible labour that can move between constraints and non-constraints. Failure to manage the capacity usage of non-bottlenecks. Hence, ensuring high labour utilisations.**

The use of flexible labour within DBR environments is essential to their operational effectiveness, for maximising operator utilisation and minimising in-process inventory, since such flexibility makes possible:

- Use of bottlenecks to their full capacity even when bottleneck and constraint processes 'shift' due to changing product mixes.
- Operators at non-constraint processes can be moved both between processes, when required, and at times when processes need to be operated or allowed to be idle.

The ability of the genetic algorithm-based solution method developed during this project to resolve the above DBR failure mechanism is through its ability to generate information that can be used to manage finite labour requirements. An example demonstrating this ability is to examine the effects of changing product mixes. Examination of Experiments 4.4 and 6.2 results in Table 6.4, both of which provide optimum throughput levels for their respective product mixes, show the following changes in machine utilisation take place, i.e.:

- Machine 1 - %Working increases from 43.0% to 92.5%.
- Machine 2 - %Working increases from 23.4% to 73.2%.
- Assembly A+B - %Working decreases from 54.1% to 44.0%.
- Assembly B+C - %Working increases from 49.21% to 84.2%.
- Machine 1 - %Waiting decreases from 55.0% to 5.0%.
- Machine 2 - % Waiting decreases from 75.0% to 25.0%.
- Assembly A+B - %Waiting increases from 45.0% to 55.0%.
- Assembly B+C - % Waiting decreases from 50.0% to 15.0%.

Hence it can be expected that additional resources would be required Machine 1 should product mixes change, and similarly at Machine 2 and Assemble B+C whilst resources may need to be moved from Assembly A+B to these processes. Examination of the %Waiting results indicates that staffing of both assembly processes needs careful management to ensure that excessive operator resources are not wasted through these processes lying idle due to lack of work.

In addition to daily management of resource the optimum operating conditions for a range of product mix scenarios could be generated to provide essential information for designing and implementing long term training programmes designed to increase the process flexibility of shop floor staff.

3. **Failure to develop adequate plans and job schedules that will maximise the bottleneck capacity, and/or provide responsive re-planning. Failure due to an inability to re-plan schedules, batch sizes and buffers sufficiently frequently to ensure that throughput is always maximised through best use of bottlenecks even though such bottlenecks may not always be explicitly known. Failure through the use of fixed lead times to schedule the bottleneck can lead to increased work-in-progress.**

The method of constructing production schedules within a DBR system involves firstly scheduling the bottleneck work area to maximise its capacity usage or ‘profit making ability’ and then to use this schedule to backward-schedule operations up-stream of the bottleneck and to forward schedule those operations downstream. This is further complicated by the need to provide for the specific needs of processes that for example undertake assemble operations and would lie idle if any one component needed in the assembly process was not available. In large, complex manufacturing environments such scheduling was undertaken by expensive and data-hungry computer systems which required updating with shop floor information frequently and accurately. These needs required excessive investment in shop floor data collection systems and/or operators to manually collect and update data. Such systems have rapidly become obsolete due to these reasons. The GA method developed has the potential to overcome these problems by its ability to simultaneously generate schedules for all processes as well as the buffer sizes and batch sizes they require to be effective.

The ability of the genetic algorithm-based solution method developed during this project to resolve the above DBR failure mechanism is through its ability to provide frequent reschedules, that maximises throughput levels, without the need to explicitly identify the bottleneck process. This avoids the need, which often occurs in practice, of waiting until work begins to build-up in front of the new bottleneck process before taking action to ensure the process capacity at this process is fully used. Such action cannot be successful unless, along with job schedules, the process and transfer batch sizes and buffer positions and sizes are also planned effectively. An example demonstrating this ability are the results obtained, Table 6.5, when constraining the Transfer Batch Size (TBS) to 1 unit which resulted in the use of smaller processing batch sizes then all other experiments, i.e. minimum batch size = 10 units, maximum batch size = 30 units and average batch size = 19 units. Experiments 1.4, 2.3, 3.2 and 4.1, Table 6.4, each has a unique combination of job sequences for Machine 1 and Machine 2. Examining these results shows that those for Experiment 2.3 possess the highest throughput level, i.e. the genetic algorithms has successfully found the optimum combination of job sequences and batch and buffer conditions for yielding maximum throughput levels.

Table 6.5: Results Table Transfer Batch = 1

TRANSFER BATCH SIZE = 1								
Product Mix	**Exp No**	**B1**	**B2**	**B3**	**B4**	**B5**	**Throughput**	**Process batch size**
AB AB BC	**1.4**	24	22	14	7	18	1262	20
	2.3	7	12	18	8	5	1390	15
	3.2	28	25	17	14	18	989	10
	4.1	5	10	17	5	4	1380	25
AB BC BC	**5.4**	28	32	18	9	23	1443	18
	6.3	7	15	23	10	7	1818	25
	7.2	28	31	22	18	23	1268	30
	8.1	5	13	22	8	7	957	10

4. **Failure to calculate processing and transport batch sizes and buffer quantities and their locations correctly leading to bottleneck starvation and hence loss of system throughput. Failure due to the inability to identify strategic planning points within the system, i.e. bottlenecks, constraint resources, assembly points, disassembly points, particularly when such positions may alter with changes in product mix and customer demand.**

Ideal maximum buffer size and processing batch sizes for a process is that which:

i) Ensures that bottleneck and constraint processes do not lose capacity for example through excessive set-up time, i.e. are able to maximise use of their available capacity.

ii) Does not create 'lean wastes' through inventory lying idle on the shop floor, i.e. through creating work-in-progress.

iii) Enables an acceptable customer-related 'delivery lead time' to be achieved.

These requirements are the same for transfer batch sizing which also possesses an addition constraint, i.e. the physical problems in moving materials between processes. Here the physical size and/or weight of the component may limit transfer batch sizes as well as the type of equipment and its availability required to provide the transport. Overhead cranes, for example, would be expected to service many individual processes and would hence lead to less frequent moves between individual pairs of processes being possible and hence the need for larger transfer batch sizes.

Examination of the results shown in Table 6.6 illustrates how the GA method developed enables all above requirements to be achieved, i.e.:

- **Ensures that bottleneck and constraint processes do not lose capacity for example through excessive set-up time, i.e. are able to maximise use of their available capacity.**

For each of the experiments within product mix AB:BC:BC, i.e. Experiments 5.3, 6.4, 7.1, and 8.2, the buffer sizes vary considerably from the smallest of 13 units to the largest of 80 units as do the batch sizes between 10 and 30. The genetic algorithm process is determining each individual buffer size with the option of setting this value to zero indicating that no buffer inventory would be needed and the batch sizes where the minimum value is 1 unit. When the detailed utilisation results for Experiments 8.2 and 6.4 are examined in Table 6.7 it can be seen that the utilisation of the bottleneck processes in each experiment is fully used, i.e.:

a. Experiment 8.2 - Machine 2 %Working = 79.8% and %Changeover = 20.1% which totals 99.9%, and
b. Experiment 6.4 - Machine 2 %Working = 70.9% and %Changeover = 28.1% which totals 99.0%.

- **Does not create 'lean wastes' through inventory lying idle on the shop floor, i.e. through creating work-in-progress.**

The genetic algorithm fitness function has been designed to enable the GA to seek the smallest amounts of buffer stocks and the smallest processing batch sizes that yield the maximum throughput levels. Hence, shop floor work-in-progress can be considered at minimal levels therefore minimising 'lean wastes'.

- **Enables an acceptable customer-related 'delivery lead time' to be achieved.**

Within the discrete event simulation model used within the current research lead times are determined primarily by process batch sizes and transfer batch sizes. Since these are the minimum possible to retain maximum throughput levels it can be expected that delivery lead times will also be minimised. The shorter the actual delivery lead times then the more likely that customers will find these lead times acceptable.

Table 6.6: Results Transfer Batch = 10

TRANSFER BATCH = 10								
Product Mix	**Exp No**	**B1**	**B2**	**B3**	**B4**	**B5**	**T/Put**	**Process batch size**
AB AB BC	**1.3**	39	18	36	12	41	1325	20
	2.4	20	10	17	28	20	1459	15
	3.1	35	20	31	16	36	1038	10
	4.2	44	28	38	22	44	1490	25
AB BC BC	**5.3**	79	49	70	37	80	1515	18
	6.4	47	21	47	13	58	1963	25
	7.1	37	31	39	18	49	1370	30
	8.2	45	33	41	30	44	1004	10

Table 6.7: Experiment Comparisons Transfer Batch = 10

Experiment 8.2: Transfer Batch Size = 10 (Worst Case)					
Process Batch Size of 10					
working	Blocking & waiting	C/O	Buffer	Process	Throughput
60.0	40.0	22.5	45	Machine 1	**1004**
80.0	20.0	20.1	33	Machine 2	
45.0	55.0	0	41	Assembly A+B	
55.0	45.0	0	30	Assembly B+C	
0	0	0	44	Assembly B+C	
Experiment 6.4: Transfer Batch Size = 10 (Best Case)					
Process Batch Size = 25					
working	Blocking & waiting	C/O	Buffer	Process	Throughput
46.5	53.5	46.5	47	Machine 1	**1963**
71	29.0	28.1	21	Machine 2	
27.0	73	0	47	Assembly A+B	
36.5	63.5	0	13	Assembly B+C	
0	0	0	58	Assembly B+C	

6.2 Gaining Effective Process Synchronisation

By comparing those experiments that yielded ‘best’ and ‘worst’ throughput levels and correlations between process centre utilisation and throughput levels; new knowledge can be gained concerning how DBR processes facilitate and impede materials flow synchronisation within high variety/low volume manufacturing environments.

From the results of the experiments the following factors have been identified as affecting throughput and hence process synchronisation, i.e.:

1. As transfer batch sizes increase then:

i. Throughput levels tend to increase.

Table 6.8 reveals that when the system conditions are the same, i.e. Transfer batch = 1 and Transfer batch = 10 have the same process batch sizes; system throughput for all experiments increased as the transfer batch size increased from 1 to 10; i.e.

Experiment 8.1 transfer batch = 1 throughput = 957,

Experiment 8.2 transfer batch = 10 throughput = 1004,

Experiment 8.4 PBS = TBS transfer batch = 52 throughput = 1059.

ii. The optimum process batch sizes required to generate maximum levels of throughput increase

Table 6.8 shows that when the process batch size was equal to the transfer batch size; as PBS = TBS increased in size the throughput levels increased, but the results also indicated that there was a point where the throughput began to reduce again therefore showing the ideology of the transfer batch for increasing system flow by incrementing large process batch sizes and reducing the number of set-ups, i.e. there was an optimum transfer batch size to process batch size for a certain set of experimental conditions for maximising throughput levels, i.e. PBS = TBS:

Experiment 2.2 process batch of 22 = throughput of 1642

Experiment 6.2 process batch of 30 = throughput of 1723

Experiment 4.4 process batch of 40 = throughput of 2209

Experiment 8.4 process batch of 52 = throughput of 1059

Although product mixes must be taken into consideration.

iii. The optimum buffer sizes required to generate maximum levels of throughput increase.

Table 6.9 shows that in general as Transfer batch sizes increase the amount of units within the system will increase; this has been shown throughout all the sets of experiments to be true, i.e.

Transfer batch = 1; Total system buffers were between 41 and 110 units,

Transfer batch = 10; Total system buffers were between 95 and 314 units,

PBS = TBS; Total system buffers were between 246 and 431 units.

PBS = TBS Experiment 3.3 with a transfer batch of 55 was the highest of all experiments at 431.

Transfer batch = 1 Experiment 4.1 was the lowest total system buffer of 41 from all experiments.

Table 6.8: Transfer Batch Size v Throughput

	Nominal	TBS = 1		TBS = 10		PBS = TBS	
Product Mix	**Exp No**	**PBS**	**T/Put**	**PBS**	**T/Put**	**PBS**	**T/Put**
AB AB BC	**1**	20	1262	20	1325	35	1409
	2	15	1390	15	1459	22	1642
	3	10	989	10	1038	55	1244
	4	25	1380	25	1490	30	1723
AB BC BC	**5**	18	1443	18	1515	48	1545
	6	25	1818	25	1963	40	2209
	7	30	1268	30	1370	45	1340
	8	10	957	10	1004	52	1059

Table 6.9: Transfer Batch Size v Total system Buffer

	Nominal	TBS = 1		TBS = 10		PBS = TBS	
Product Mix	**Exp No**	**PBS**	**Total Buffer**	**PBS**	**Total Buffer**	**PBS**	**Total Buffer**
AB AB BC	**1**	20	85	20	145	35	371
	2	15	50	15	95	22	380
	3	10	102	10	138	55	431
	4	25	41	25	176	30	248
AB BC BC	**5**	18	110	18	314	48	290
	6	25	62	25	186	40	254
	7	30	122	30	174	45	246
	8	10	55	10	193	52	248

2. Product mix changes appear to have:

i. Little effect on the process batch sizes required to achieve maximum throughput levels.

Table 6.8 indicates that there is not a relationship between the product mix and process batch sizes, i.e. PBS = TBS AB BC BC has process batches ranging from 40 to 52 and within that range was the largest and smallest throughputs for all the whole set of experiments. Experiment 8.4 had the largest process batch size of 52 and the lowest throughput of 1059 units and 6.2 had the smallest process batch size of 40 with the highest throughput of 2209 units.

Comparing this with set of experiments Transfer of 10 the scenario was reversed, i.e. job sequences AB BC BC had a process batch size range from 10 to 30, but experiment 8.2 with a process batch size of 10 had a throughput of 1004 and experiment 6.4 with a process batch size of 25 had the highest throughput of 1963 units.

ii. A significant effect on the maximum throughput possible.

The product mix changes for each set of experiments show a definite trend on the effect of the throughput levels, e.g. Figure 6.1.

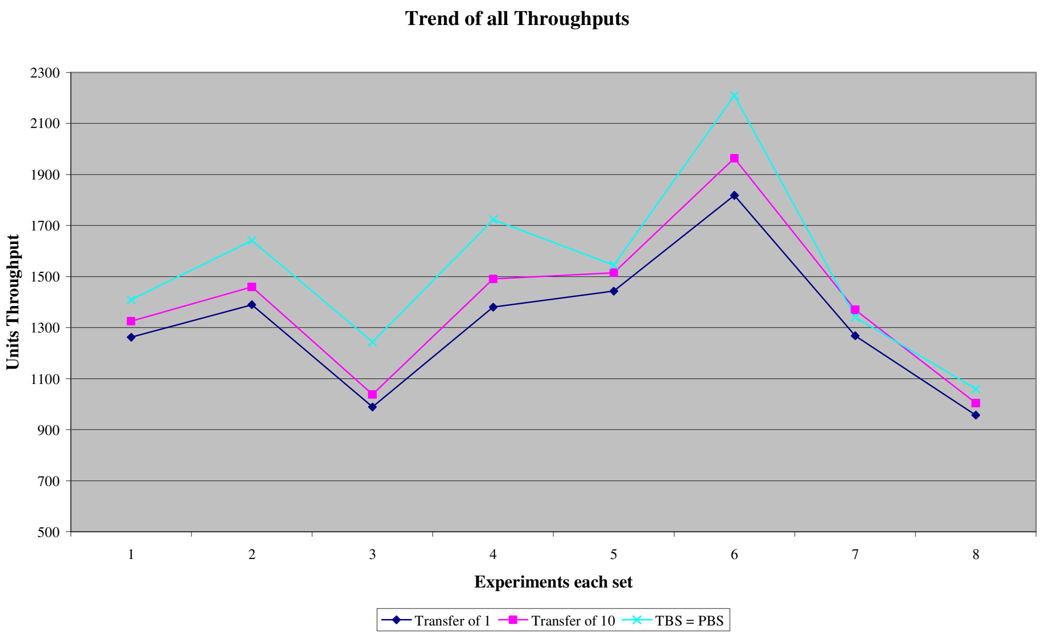

Figure 6.1: Chart of Throughput Trends all Experiments

iii. A significant effect on the buffer sizes required to achieve maximum throughput levels.

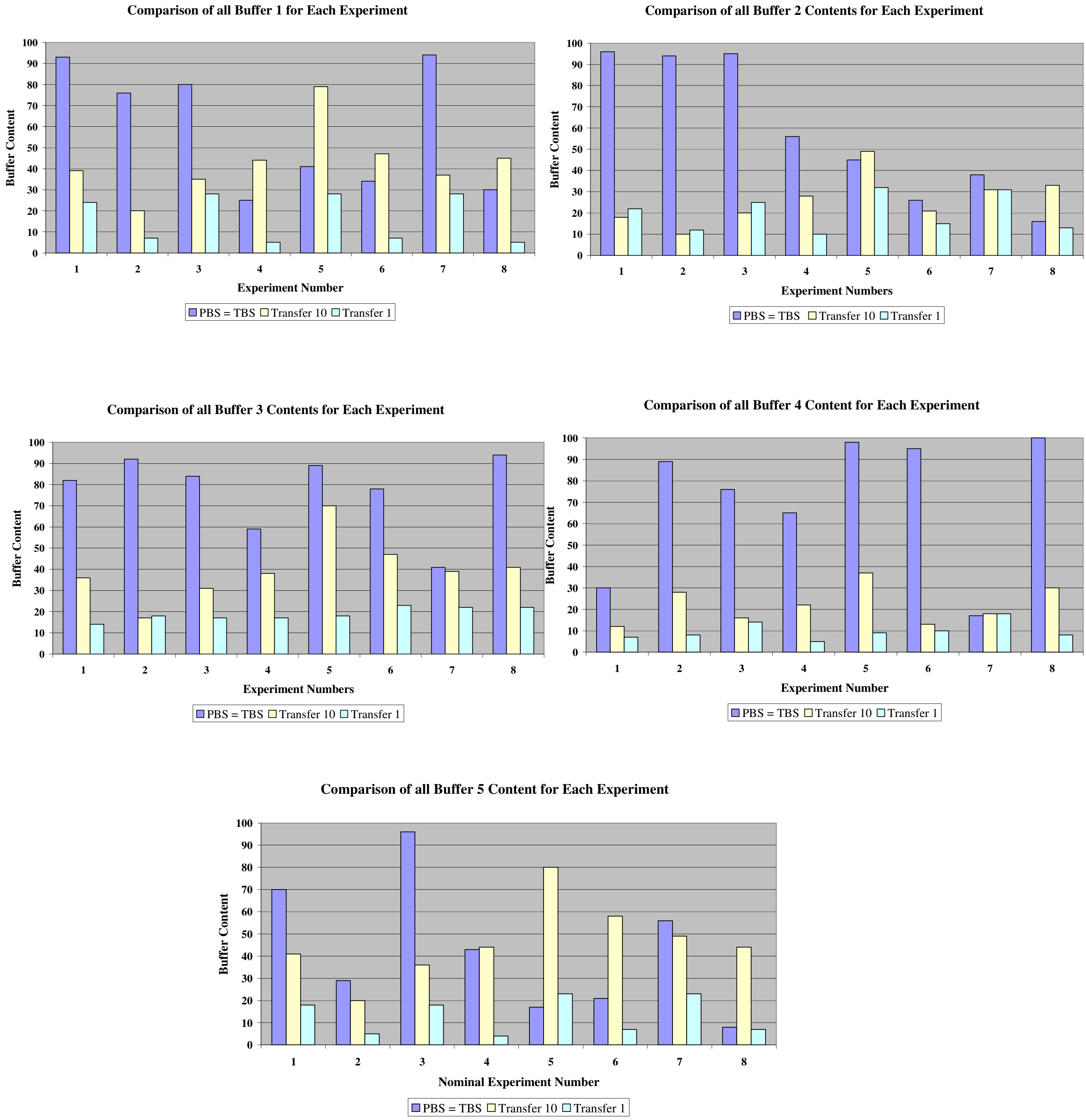

Figure 6.2: Comparisons of All Buffers

Figure 6.2 shows that each buffer was affected by the change in product mix to achieve the best throughput levels for each scenario. Looking at figure 6.2, it can be seen that for PBS = TBS the buffers for process 1 and process 2 have been affected considerably between experiment 2.2 and 4.4 for example, buffer 1 has three times the quantity and buffer 2 nearly twice the quantity for experiment 2.2 than experiment 4.4, table 6.2 shows the figures in more detail.

3. Job sequence changes appear to have:

i. Little effect on the process batch sizes required to achieve maximum throughput levels.

As explained in point 2.i. product mix change, there is also no evidence of an effect on the process batch sizes from a job sequence change.

ii. A significant effect on the maximum throughput possible.

Job sequence changes for all experiments have shown that the same job sequence of AB BC BC provides the best throughput. For example, Table 6.6 Transfer batch = 10 indicates that the best case for AB AB BC is affected by blocking and waiting at process 1 and 2, this has resulted in smaller possible buffer sizes before the assembly processes. The best case for AB BC BC has resulted in far less blocking and waiting and therefore assembly buffers 3,4 and 5 are able to provide more mating parts for a higher throughput. AB BC BC also provides the worst throughput as the product mix changes, see point iii below for best throughput details.

Transfer batch = 1

Experiment 2.3, job sequence AB AB BC best throughput,

B1 = 7, B2 = 12, B3 = 18, B4 = 8, B5 = 5 achieving a throughput of 1390 units.

Experiment 3.2, job sequence AB AB BC worst throughput,

B1 = 28, B2 = 25, B3 = 17, B4 = 14, B5 = 18 achieving a throughput of 989 units.

Transfer batch = 10

Experiment 4.2, job sequence AB AB BC best throughput,

B1 = 44, B2 = 28, B3 = 38, B4 = 22, B5 = 44 achieving a throughput of 1490 units.

Experiment 3.1, job sequence AB AB BC worst throughput,

B1 = 35, B2 = 20, B3 = 31, B4 = 16, B5 = 36 achieving a throughput of 1038 units.

PBS = TBS

Experiment 4.4, job sequence AB AB BC best throughput,

B1 = 25, B2 = 56, B3 = 59, B4 = 65, B5 = 43 achieving a throughput of 1723 units.

Experiment 3.3, job sequence AB AB BC worst throughput,

B1 = 80, B2 = 95, B3 = 84, B4 = 76, B5 = 96 achieving a throughput of 1244 units.

iii. A Significant effect on the buffer sizes required to achieve maximum throughput levels.

It can be seen in tables 6.5, 6.7 and 6.9 that for the transfer batches of 1 and 10, job sequence AB AB BC has a lower maximum and minimum buffer size for all buffers than job sequence AB BC BC. PBS = TBS which has larger process batch sizes/transfer batch sizes, the lower buffer sizes are on job sequence AB BC BC and can be seen graphically in figures 6.9 to 6.13, i.e.

Transfer batch = 1

Experiment 6.3, job sequence AB BC BC best throughput,

B1 = 7, B2 = 15, B3 = 23, B4 = 10, B5 = 7 achieving a throughput of 1818 units.

Experiment 8.1, job sequence AB BC BC worst throughput,

B1 = 5, B2 = 13, B3 = 22, B4 = 8, B5 = 7 achieving a throughput of 957 units.

Transfer batch = 10

Experiment 6.4, job sequence AB BC BC best throughput,

B1 = 47, B2 = 21, B3 = 47, B4 = 13, B5 = 58 achieving a throughput of 1963 units.

Experiment 8.2, job sequence AB BC BC worst throughput,

B1 = 45, B2 = 33, B3 = 41, B4 = 30, B5 = 44 achieving a throughput of 1004 units.

PBS = TBS

Experiment 6.2, job sequence AB BC BC best throughput,

B1 = 34, B2 = 26, B3 = 78, B4 = 95, B5 = 21 achieving a throughput of 2209 units.

Experiment 8.4, job sequence AB BC BC worst throughput,

B1 = 30, B2 = 16, B3 = 94, B4 = 100, B5 = 8 achieving a throughput of 1059 units.

4. **As change-over times increase they appear to have:**

   i. **Little effect on the process batch sizes required to achieve maximum throughput levels.**

Table 6.10 shows that change-over time has no effect on the process batch sizes for increasing the throughput levels. Experiment 4.1 has C/O 12.56 for process 1 and 17.23 for process 2 with a process batch size of 25 and a throughput of 1380. Experiment 6.3 has C/O of 24.54 for process 1 and 17 for process 2 with the same process batch of 25 and a throughput of 1818, indicating that the C/O time did not have an effect on the process batch size when there was an increase.

   ii. **A significant effect on the maximum throughput possible.**

Again in Table 6.10;

Experiment 4.1 has C/O 12.56 for process 1 and 17.23 for process 2 and a throughput of 1380.

Experiment 6.3 has C/O of 24.54 for process 1 and 17 for process 2 and a throughput of 1818.

But because the job sequences have an effect on throughput; reference point 3.ii, they must be examined separately, and table 6.8 shows that for both sets of job sequences the increase in C/O time tends to have an effect of reducing the throughput levels. The best set of results to see the effect of C/O is Transfer of 1 as it is less complex, not forgetting that there are other factors also affecting throughput levels.

iii. **A significant effect on the buffer sizes required to achieve maximum throughput levels.**

Table 6.4 shows that there is an effect on the preceding buffers to the change-over processes, i.e.

Sequence AB BC BC Experiment 8.4 C/O = 14.8 for process 1 with 22% waiting time and a buffer of 30. Process 2 had a C/O of 17.8 with a waiting time of 18% and a buffer of 16, the throughput was 957 units.

Experiment 6.2 process 1 had a C/O of 4.6 with a waiting time of 7.5% and a buffer of 34, and process 2 had a C/O of 25.7, a waiting time of 27% and a buffer of 26, the throughput was 2209 units.

Table 6.10: The Effect of Change-over Transfer = 1

TRANSFER BATCH SIZE OF ONE							
Exp 1.4				**Exp 5.4**			
Process Batch Size of 20				***Process Batch Size of 18***			
C/O	*Buffer*	*Process*	*T/put*	***C/O***	*Buffer*	*Process*	*T/put*
25	24	Machine 1	**1262**	**12.56**	5	Machine 1	**1380**
22	22	Machine 2		**17.23**	10	Machine 2	
0	14	Assembly A+B		0	17	Assembly A+B	
0	7	Assembly B+C		0	5	Assembly B+C	
0	18	AB or BC		0	4	AB or BC	
Exp 2.3				**Exp 6.3**			
Process Batch Size of 15				***Process Batch Size of 25***			
C/O	*Buffer*	*Process*	*T/put*	***C/O***	*Buffer*	*Process*	*T/put*
19.54	7	Machine 1	**1390**	**24.54**	7	Machine 1	**1818**
12.65	12	Machine 2		**17**	15	Machine 2	
0	18	Assembly A+B		0	23	Assembly A+B	
0	8	Assembly B+C		0	10	Assembly B+C	
0	5	AB or BC		0	7	AB or BC	
Exp 3.2				**Exp 7.2**			
Process Batch Size of 10				***Process Batch Size of 30***			
C/O	*Buffer*	*Process*	*T/put*	***C/O***	*Buffer*	*Process*	*T/put*
22	28	Machine 1	**989**	**23.21**	28	Machine 1	**1268**
9	25	Machine 2		**18.96**	31	Machine 2	
0	17	Assembly A+B		0	22	Assembly A+B	
0	14	Assembly B+C		0	18	Assembly B+C	
0	18	AB or BC		0	23	AB or BC	
Exp 4.1				**Exp 8.1**			
Process Batch Size of 25				***Process Batch Size of 10***			
C/O	*Buffer*	*Process*	*T/put*	***C/O***	*Buffer*	*Process*	*T/put*
12.56	5	Machine 1	**1380**	**17.87**	5	Machine 1	**957**
17.23	10	Machine 2		**27.54**	13	Machine 2	
0	17	Assembly A+B		0	22	Assembly A+B	
0	5	Assembly B+C		0	8	Assembly B+C	
0	4	AB or BC		0	7	AB or BC	

Chapter 7 - Conclusions

7.1 Conclusions

This research has investigated the mechanisms and complexities of material flow in manufacturing systems and then compared various systems for their ability in promoting material flow. Once the most satisfactory system was identified the failure mechanisms were then identified.

i.e.:

1. Failure to locate the bottleneck of the system will result in lost throughput, or increased WIP and cycle time depending on the 'false' bottlenecks' location relative to the real bottleneck. Failure through large amounts of variance, such as rework and machine breakdowns, causing bottlenecks to shift quickly.
2. Failure to provide flexible labour that can move between constraints and non-constraints. Failure to manage the capacity usage of non-bottlenecks. Hence, ensuring high labour utilisations.
3. Failure to develop adequate plans and job schedules that will maximise the bottleneck capacity, and/or provide responsive re-planning. Failure due to an inability to re-plan schedules, batch sizes and buffers sufficiently frequently to ensure that throughput is always maximised through best use of bottlenecks even though such bottlenecks may not always be explicitly known. Failure through the use of fixed lead times to schedule the bottleneck can lead to increased work-in-progress.

4. Failure to calculate processing and transport batch sizes and buffer quantities and their locations correctly leading to bottleneck starvation and hence loss of system throughput. Failure due to the inability to identify strategic planning points within the system, i.e. bottlenecks, constraint resources, assembly points, disassembly points, particularly when such positions may alter with changes in product mix and customer demand.

The results from a DES model have been presented in this thesis that was able to address each failure mode and furthermore identify how material flow is affected by the processes within a DBR manufacturing system which has not been previously identified.

1. As transfer batch sizes increase then:

   i. Throughput levels tend to increase.

   ii. The optimum process batch sizes required to generate maximum levels of throughput increase

   iii. The optimum buffer sizes required to generate maximum levels of throughput increase.

2. Product mix changes appear to have:

   i. Little effect on the process batch sizes required to achieve maximum throughput levels.

   ii. A significant effect on the maximum throughput possible.

iii. A significant effect on the buffer sizes required to achieve maximum throughput levels.

3. Job sequence changes appear to have:

i. Little effect on the process batch sizes required to achieve maximum throughput levels.
ii. A significant effect on the maximum throughput possible.
iii. A Significant effect on the buffer sizes required to achieve maximum throughput levels.

4. As change-over times increase they appear to have:

i. Little effect on the process batch sizes required to achieve maximum throughput levels.
ii. A significant effect on the maximum throughput possible.
iii. A significant effect on the buffer sizes required to achieve maximum throughput levels.

On reflection, I have managed to achieve most of my research objectives by using a basic DBR model, and this research has highlighted that as such a model becomes more complex it also becomes more volatile and more difficult to control. Previous research into DBR systems show that it out performs most other systems when there is high system variability but how complex and volatile can the system get before it becomes ineffective? This research has also shown how small changes to schedules or product mixes can change the throughput of a system and also affect material flow to varying degrees that are not always evident in HVLV manufacturing environments.

Despite the positive previous research, I was not able to find a UK company that uses DBR methodology to use as data for my model, so a more complex and robust model is needed to realistically have a valid use in industry. There is a great deal of relevance to this research to identify the details behind the proven theory that may be preventing DBR from being a more widely used system within manufacturing, i.e. the failure mechanisms that have been addressed and described in chapter 6.1.2.

7.2 Future Work

Following the experiments described in this thesis, expansion of the model to examine and compare the outcomes of a more complex model, i.e. increased variability and product variety is required to validate the robustness of the model and confirm the soundness of the existing experimental results, reference the assumptions laid-out in chapter 4.

Stage 2 could entail examining the effect of material flow through a DBR system by increasing process cycle times and further DBR system validation by adding random break-downs to examine how the system maintains throughput compared to break-down free periods of time. Random material input at model entry using supply chain buffers could be investigated by expanding the use of the model to deal with supply chain disruptions.

Stage 3 which would have an increased benefit to current industry in terms of premium products against value products that are manufactured on the same flow lines by focusing on revenue; this could lead on to the fact that it is not always the highest throughput that generates the best revenue, as described in chapter 6, the flexibility of the GA solution method makes it possible to convert the ‘throughput-based’ fitness function used within the current research into a ‘cost-based’ and/or ‘profit-based’ fitness function and so achieve the original aims of OPT.

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Appendix A: 36 Array

L 36 ARRAY

PROCESS

A_1	1	1	1	1	1	1	1	1	1	1	1	1
B_1	1	1	1	1	1	1	1	1	1	2	2	2
C_1	1	1	1	1	1	1	2	2	2	1	1	1
D_1	A	B	C	A	B	C	A	B	C	A	B	C
E_1	A	B	C	A	B	C	A	B	C	A	B	C
F_1	A	B	C	A	B	C	B	C	A	C	A	B
n.	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***

NUMBER OF RUNS

PROCESS

A_1	1	1	1	1	1	1	2	2	2	2	2	2
B_1	2	2	2	2	2	2	1	1	1	1	1	1
C_1	2	2	2	2	2	2	2	2	2	2	2	2
D_1	A	B	C	A	B	C	A	B	C	A	B	C
E_1	B	C	A	B	C	A	B	C	A	B	C	A
F_1	C	A	B	C	A	B	A	B	C	B	C	A
n.	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***

NUMBER OF RUNS

PROCESS

A_1	2	2	2	2	2	2	2	2	2	2	2	2
B_1	1	1	1	2	2	2	2	2	2	2	2	2
C_1	1	1	1	2	2	2	1	1	1	1	1	1
D_1	A	B	C	A	B	C	A	B	C	A	B	C
E_1	C	A	B	C	A	B	C	A	B	C	A	B
F_1	B	C	A	B	C	A	C	A	B	A	B	C
n.	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***	***33***	***34***	***35***	***36***

NUMBER OF RUNS

Appendix B: ARRAY 16 Throughput and Buffer Results

	1			2			3			4		
Customer Demand	AB AB AB BC			AB AB AB BC			AB AB AB BC			AB AB AB BC		
A OR B	A	**Buffer 1**	93	A	**Buffer 1**	93	B	**Buffer 1**	43	B	**Buffer 1**	43
B OR C	B	**Buffer 2**	100	B	**Buffer 2**	100	C	**Buffer 2**	99	C	**Buffer 2**	99
		Buffer 3	99		**Buffer 3**	99		**Buffer 3**	47		**Buffer 3**	47
		Buffer 4	89		**Buffer 4**	89		**Buffer 4**	56		**Buffer 4**	56
		Buffer 5	96		**Buffer 5**	96		**Buffer 5**	89		**Buffer 5**	89
Throughput	**1276**	**Total**	**477**	**1276**	**Total**	**477**	**1573**	**Total**	**334**	**1573**	**Total**	**334**

	5			6			7			8		
Customer Demand	AB BC AB AB			AB BC AB AB			AB BC AB AB			AB BC AB AB		
A OR B	A	**Buffer 1**	59	A	**Buffer 1**	56	B	**Buffer 1**	57	B	**Buffer 1**	57
B OR C	B	**Buffer 2**	95	B	**Buffer 2**	95	C	**Buffer 2**	49	C	**Buffer 2**	49
		Buffer 3	100		**Buffer 3**	100		**Buffer 3**	4		**Buffer 3**	4
		Buffer 4	100		**Buffer 4**	100		**Buffer 4**	77		**Buffer 4**	77
		Buffer 5	25		**Buffer 5**	25		**Buffer 5**	45		**Buffer 5**	45
Throughput	**1073**	**Total**	**379**	**1073**	**Total**	**376**	**1762**	**Total**	**232**	**1762**	**Total**	**232**

	9			10			11			12		
Customer Demand	AB AB BC AB			AB AB BC AB			AB AB BC AB			AB AB BC AB		
A OR B	A	**Buffer 1**	58	A	**Buffer 1**	58	B	**Buffer 1**	25	B	**Buffer 1**	25
B OR C	C	**Buffer 2**	64	C	**Buffer 2**	64	B	**Buffer 2**	56	B	**Buffer 2**	56
		Buffer 3	34		**Buffer 3**	34		**Buffer 3**	59		**Buffer 3**	59
		Buffer 4	84		**Buffer 4**	84		**Buffer 4**	65		**Buffer 4**	65
		Buffer 5	37		**Buffer 5**	37		**Buffer 5**	43		**Buffer 5**	43
Throughput	**1946**	**Total**	**277**	**1946**	**Total**	**277**	**1723**	**Total**	**248**	**1723**	**Total**	**248**

	13			14			15			16		
Customer Demand	BC AB AB AB			BC AB AB AB			BC AB AB AB			BC AB AB AB		
A OR B	A	**Buffer 1**	72	A	**Buffer 1**	72	B	**Buffer 1**	50	B	**Buffer 1**	50
B OR C	C	**Buffer 2**	94	C	**Buffer 2**	94	B	**Buffer 2**	60	B	**Buffer 2**	60
		Buffer 3	73		**Buffer 3**	73		**Buffer 3**	37		**Buffer 3**	37
		Buffer 4	25		**Buffer 4**	25		**Buffer 4**	39		**Buffer 4**	39
		Buffer 5	60		**Buffer 5**	60		**Buffer 5**	61		**Buffer 5**	61
Throughput	**1430**	**Total**	**324**	**1430**	**Total**	**324**	**1475**	**Total**	**247**	**1475**	**Total**	**247**